Bottomonium production in heavy ion collisions at STAR

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EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Quarkonia in the sQGP

- Debye screening of heavy quark potential
  → Quarkonia are expected to dissociate

T. Matsui, H. Satz, Phys.Lett. B178, 416 (1986)

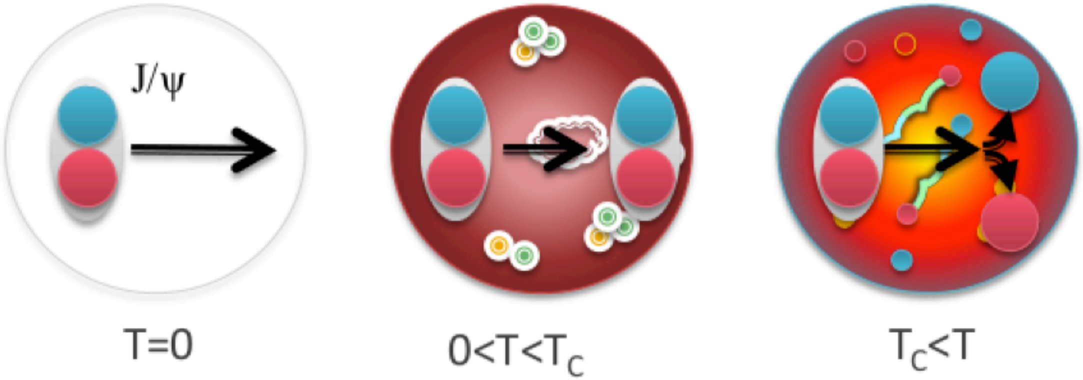

Illustration: A. Rothkopf

Charmonia ($c\bar{c}$):
J/Ψ, Ψ', χ_c

Bottomonia ($b\bar{b}$):
$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

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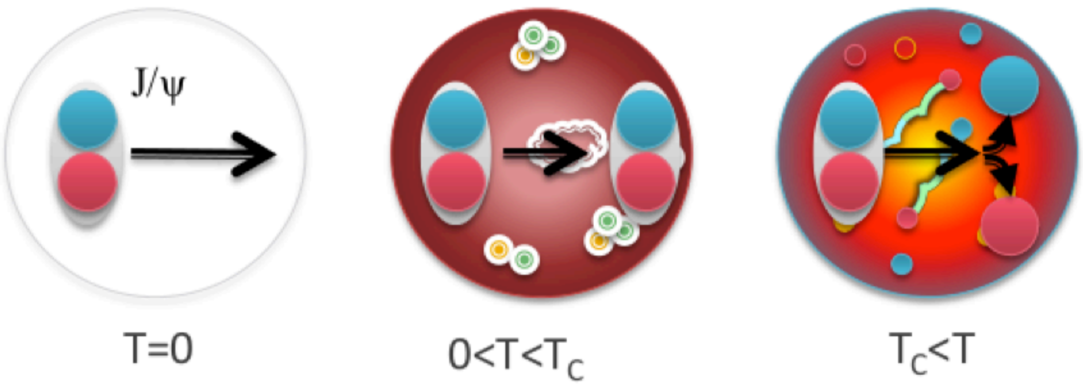

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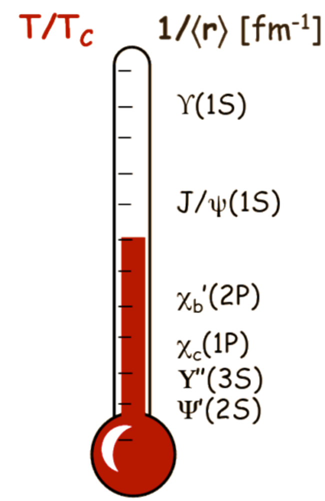
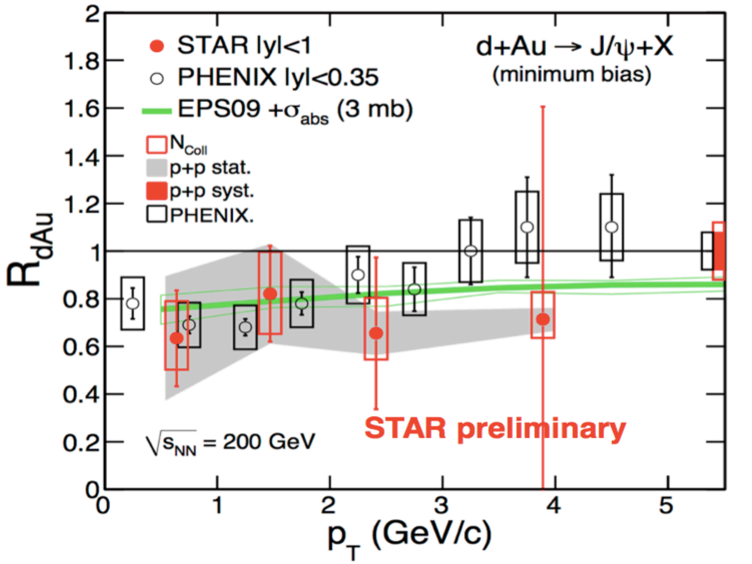


- Sequential melting: Different states dissociate at different temperatures
  Á. Mócsy, P. Petreczky, Phys. Rev. D77, 014501 (2008)

Quarkonia may serve as sQGP thermometer

Lessons from J/ψ

- Cold nuclear matter effects
  - Nuclear shadowing
    (PDF modification in the nucleus)
  - Initial state energy loss
  - Co-mover absorption



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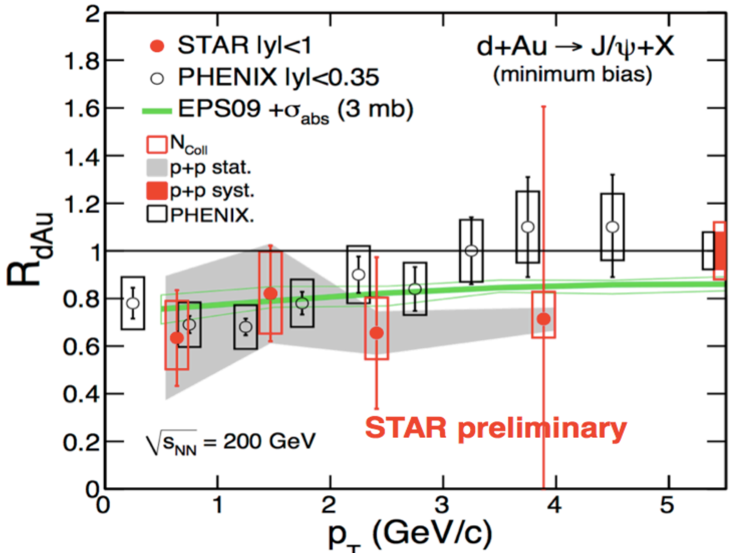
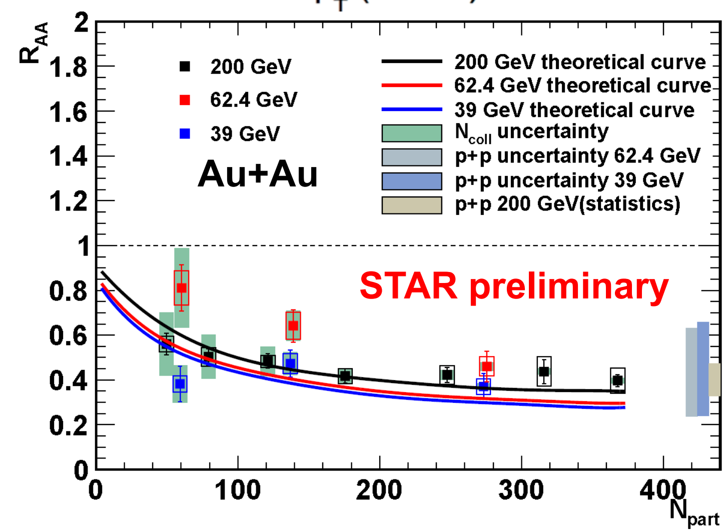
  - Coalescence of uncorrelated charm and bottom pairs.





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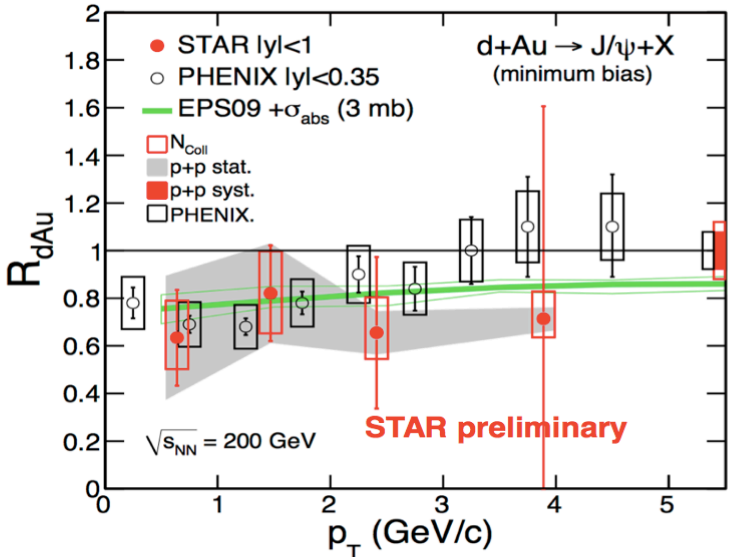
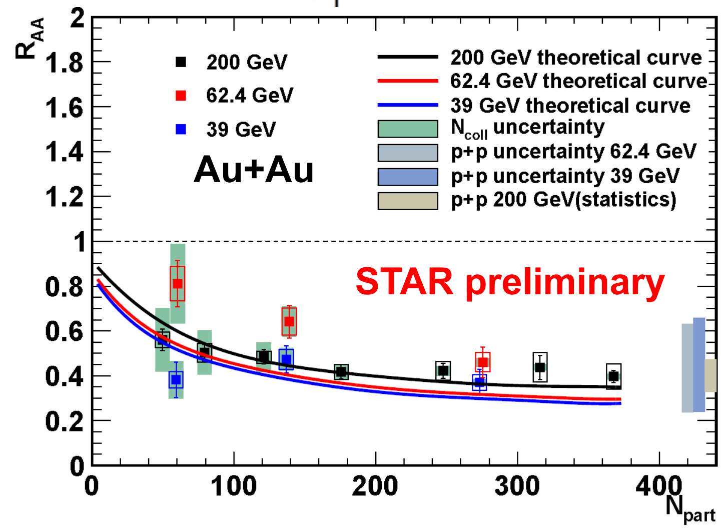
- Feed-down
  - χ_C, ψ', B-meson decay to J/ψ





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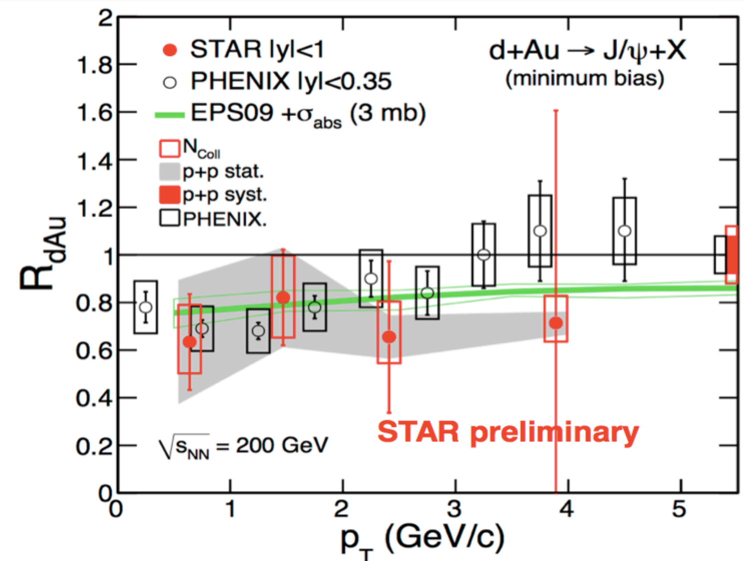
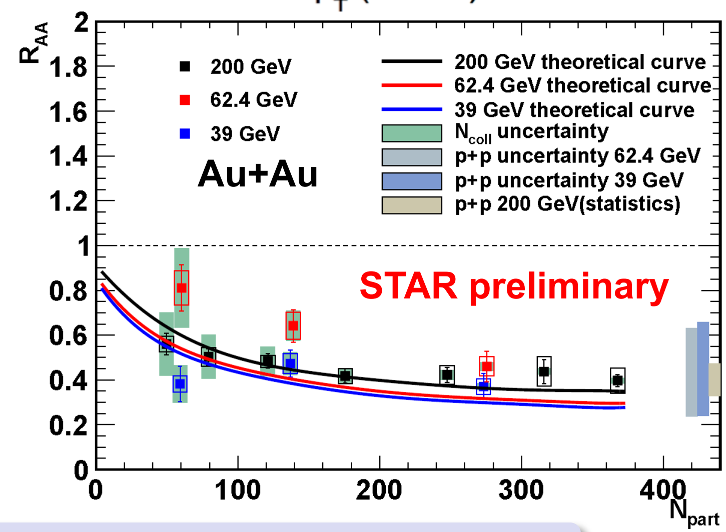




Contribution of different effects is not well understood

ϒ measurements at RHIC

- ϒ co-mover absorption is negligible at RHIC energies
  - ϒ(1S) is tightly bound, larger kinematic threshold.
  - 5-10 times smaller than for J/ψ (σ~0.2 mb)
    Lin & Ko, PLB 503 (2001) 104
- ϒ recombination → negligible at RHIC:
  - σ_{cc} ~800 μb >> σ_{bb} ~ (1-2) μb
- ϒ excited states: test sequential suppression

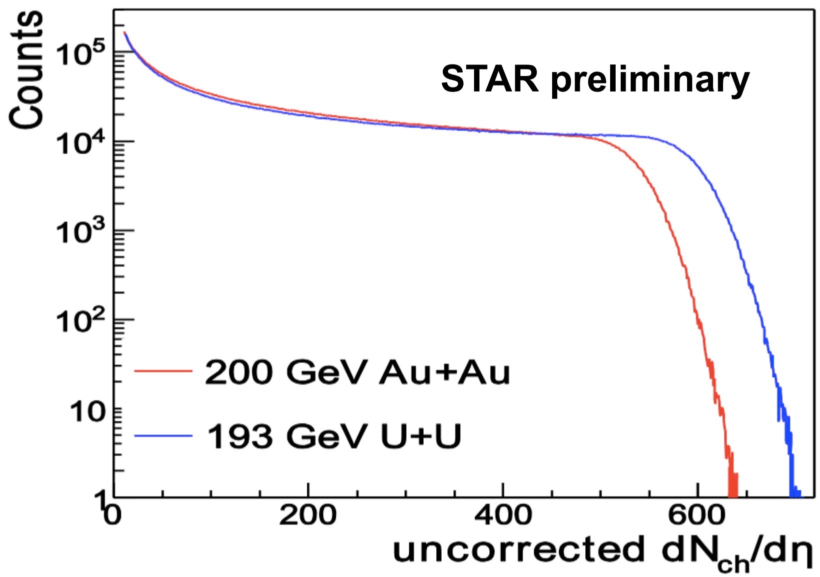
Υ measurements at RHIC

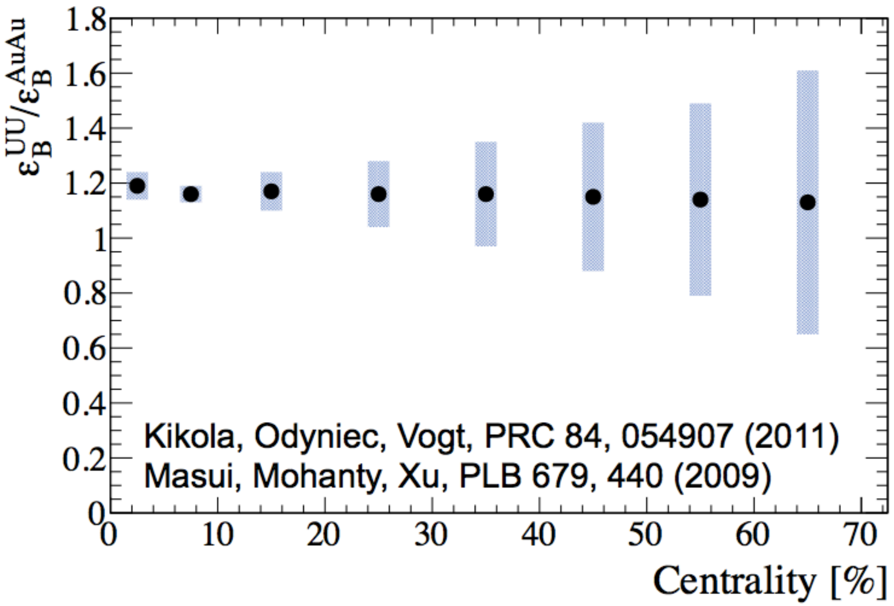
- Υ co-mover absorption is negligible at RHIC energies
  - Υ(1S) is tightly bound, larger kinematic threshold.
  - 5-10 times smaller than for J/ψ (σ~0.2 mb)
    Lin & Ko, PLB 503 (2001) 104
- Υ recombination → negligible at RHIC:
  - σ_{cc} ~800 μb >> σ_{bb} ~ (1-2) μb
- Υ excited states: test sequential suppression

Υ states provide a cleaner probe at RHIC

- Υ measurements : a challenge
  - Low production rate
  - Large acceptance, specific trigger needed
  - Feed-down still present: χ_b, Υ(2S), Υ(3S) to Υ(1S) …

U+U: Higher energy densities





RHIC $\sqrt{s_{NN}}$=193 GeV U+U data (2012)

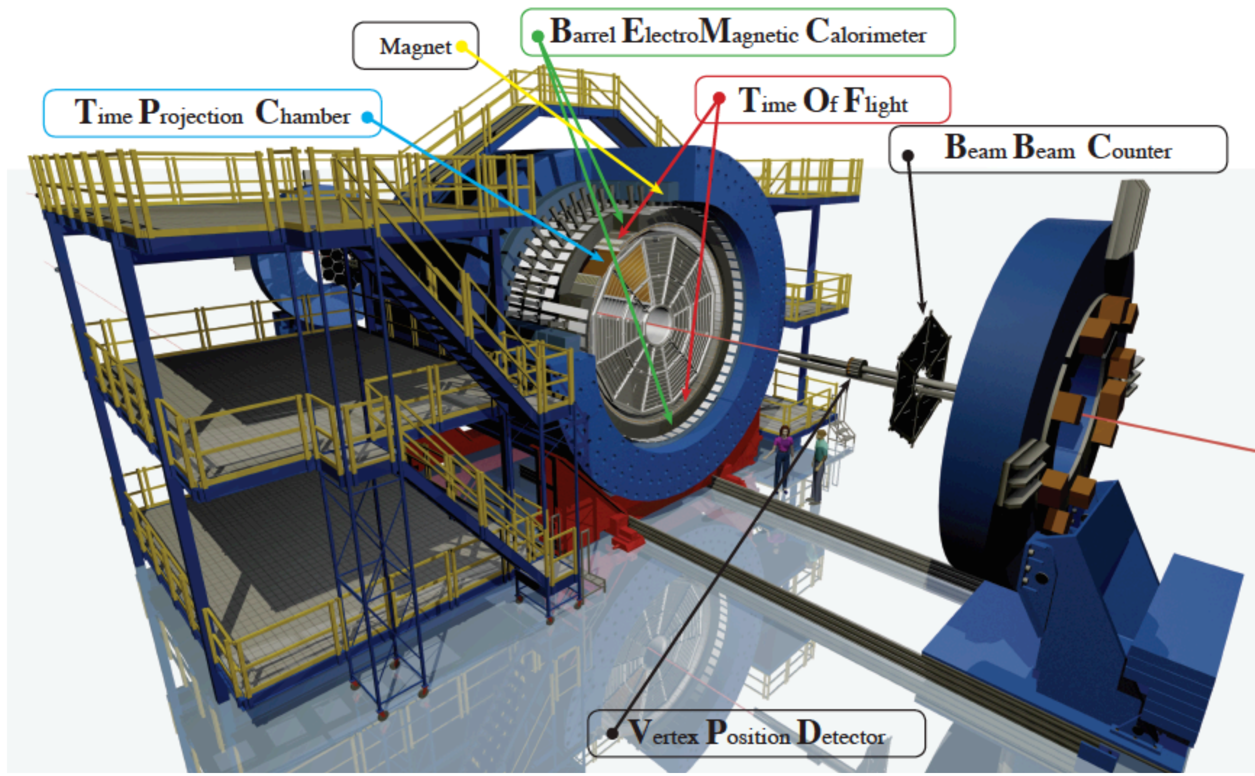
- Reach higher N_{part} than in Au+Au
- Provide higher energy density:
  ~20% more in central collisions!

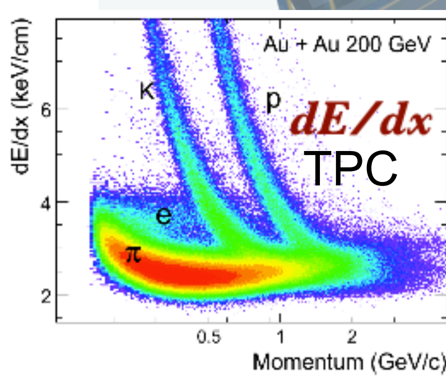
Further test of dissociation-coalescence interplay

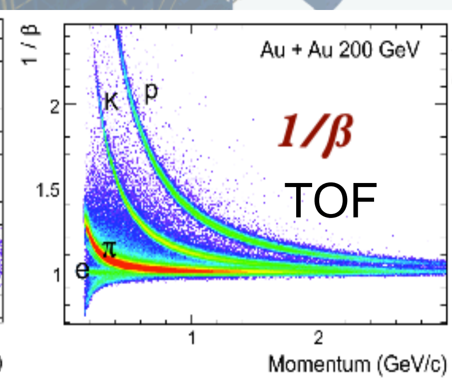
RHIC/STAR

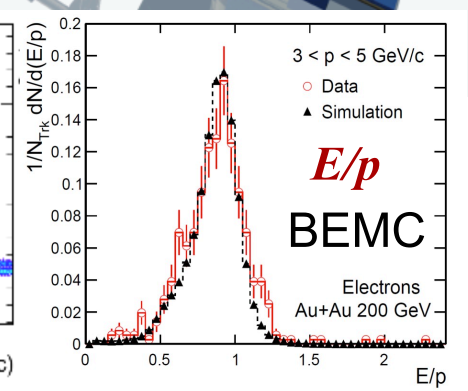
- Reconstruction:
  - $J/\psi \rightarrow e^+e^-$ ($B_{ee} \sim 6\%$)
  - $\Upsilon \rightarrow e^+e^-$ ($B_{ee} \sim 2.4\%$)
- TPC
  - dE/dx PID
  - Large acceptance, uniform in a wide energy range
- TOF
  - PID using flight time
- BEMC
  - High-p_T trigger
  - PID using E/p and shower shape
- VPD
  - Minimum bias events

Solenoidal **T**racker **A**t **R**HIC : $-1 < \eta < 1$, $0 < \phi < 2\pi$

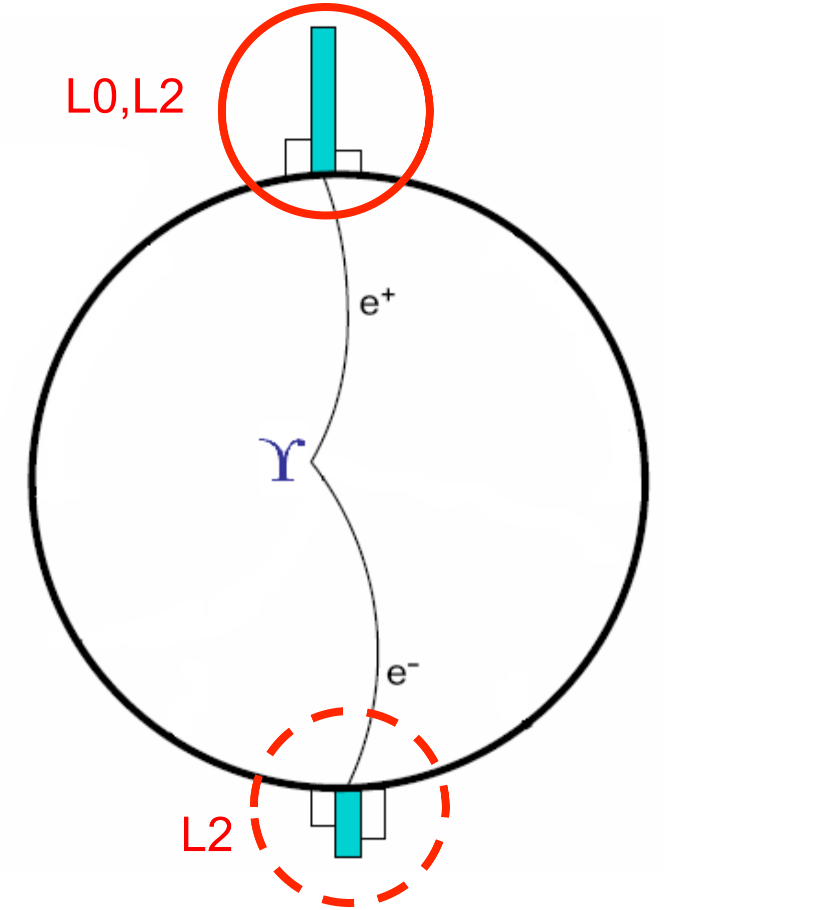


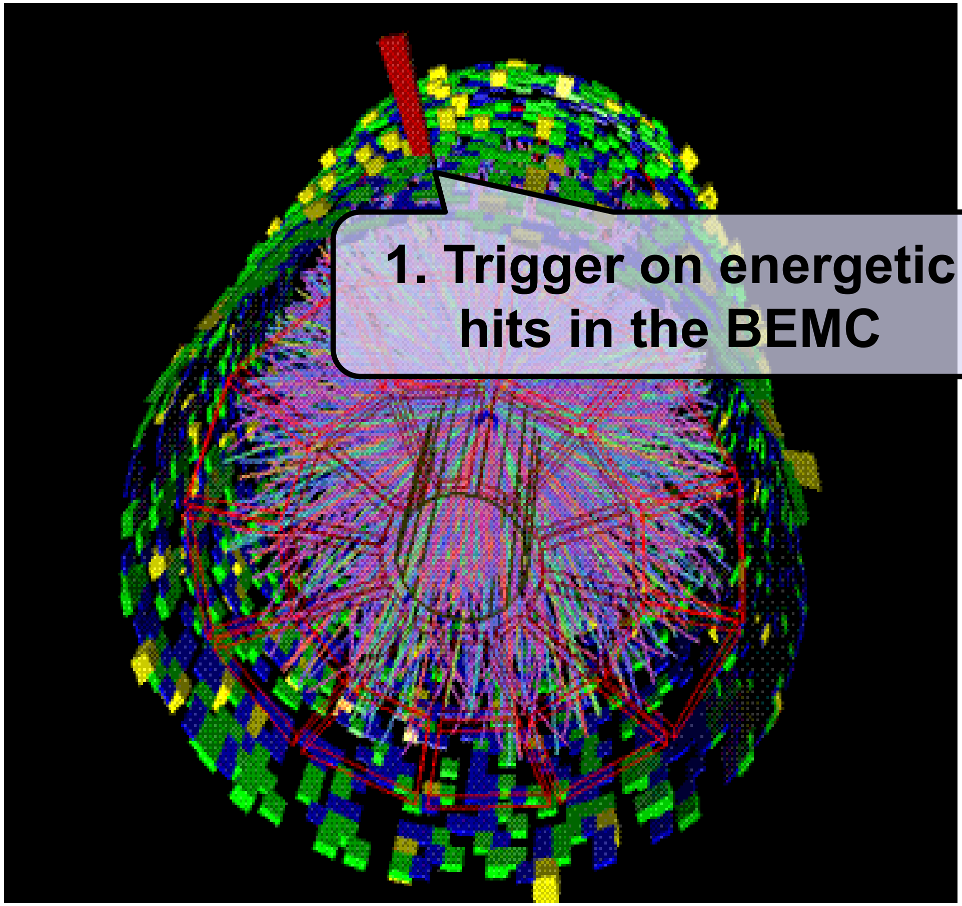






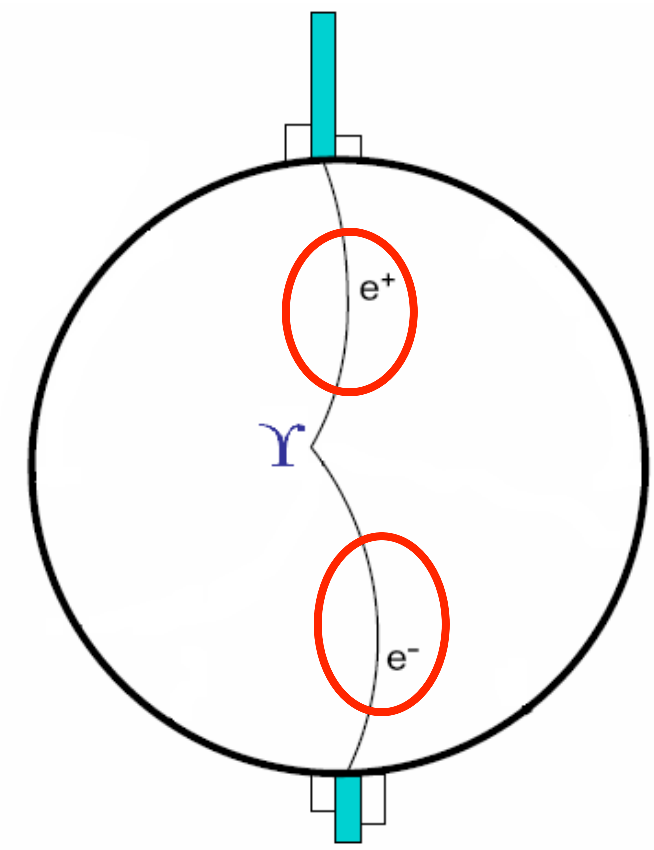
1. Triggering on Υ events

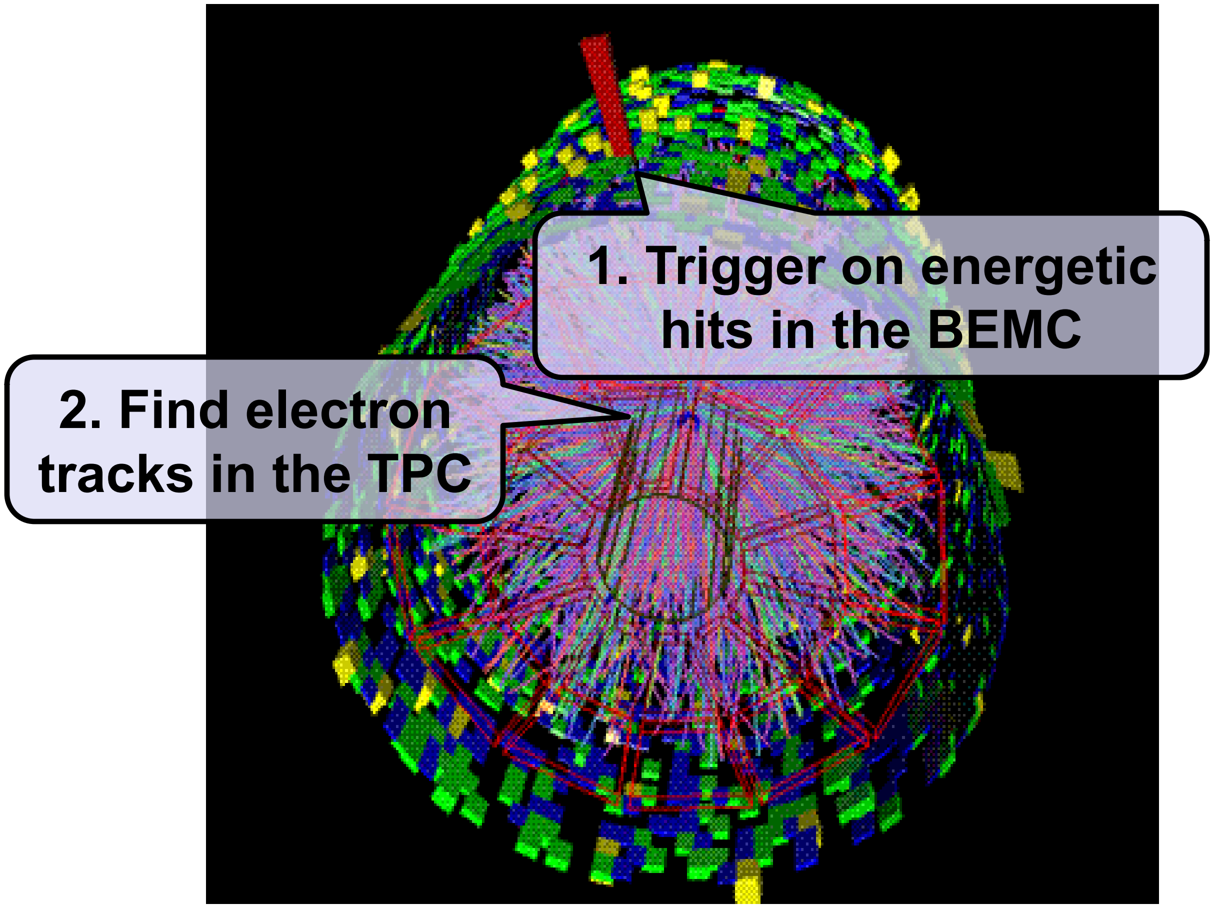




- **L0**: 'High tower trigger' saves events with a high energy hit in a Barrel Electromagnetic Calorimeter (BEMC) tower
- **L2** *in p+p and d+Au only* – software trigger: coarse reconstruction of cluster energy, opening angle, invariant mass

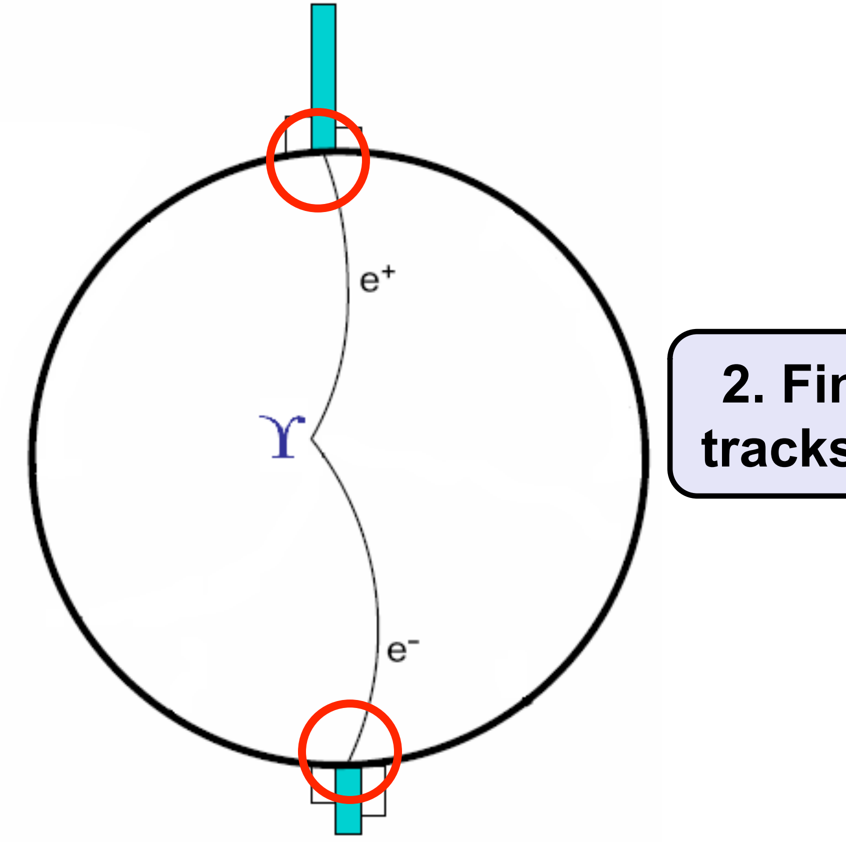
2. Finding electron tracks

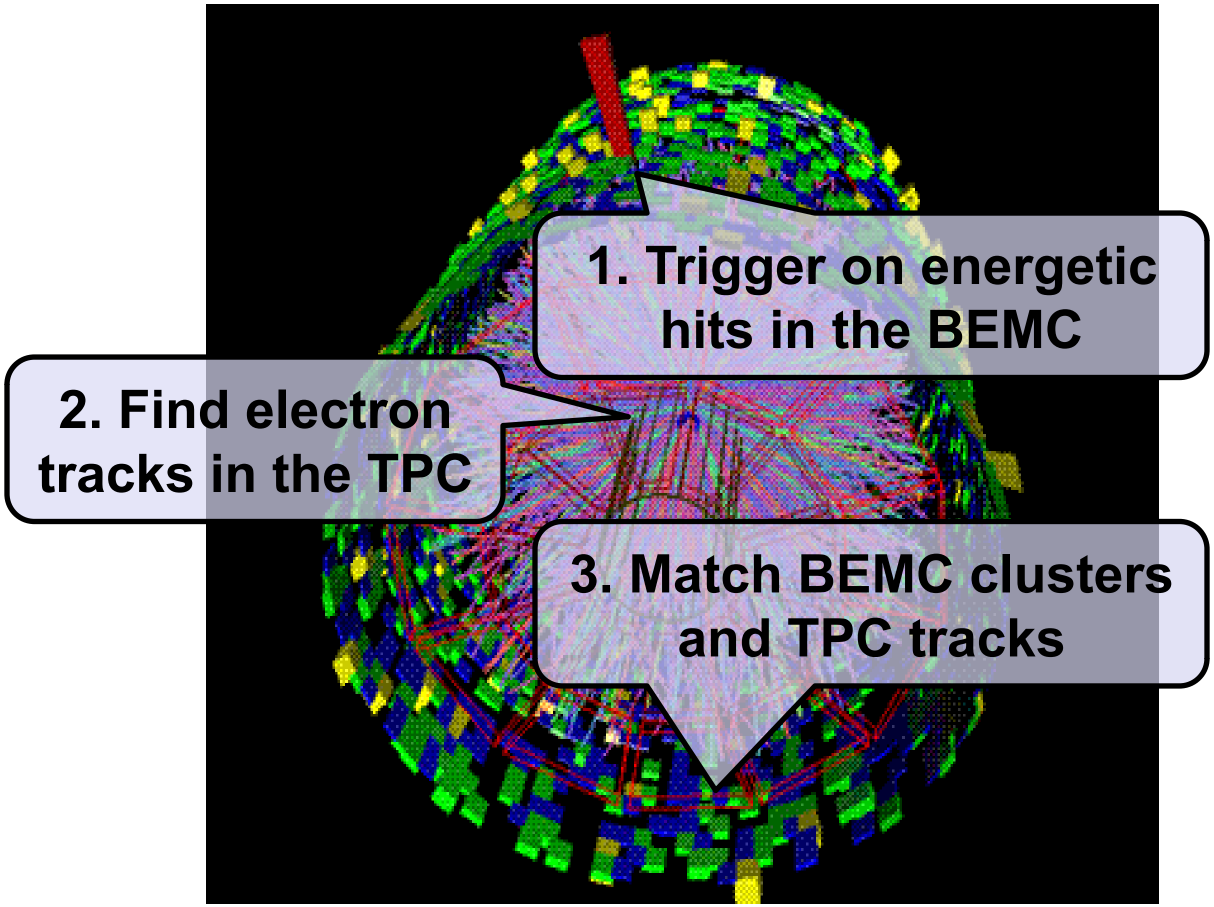




- Find tracks in the Time Projection Chamber (TPC) based on specific energy loss d*E*/dx
  $-1.2 < n\sigma_e < 3$ *(A+A analyses)*

3. Matching tracks



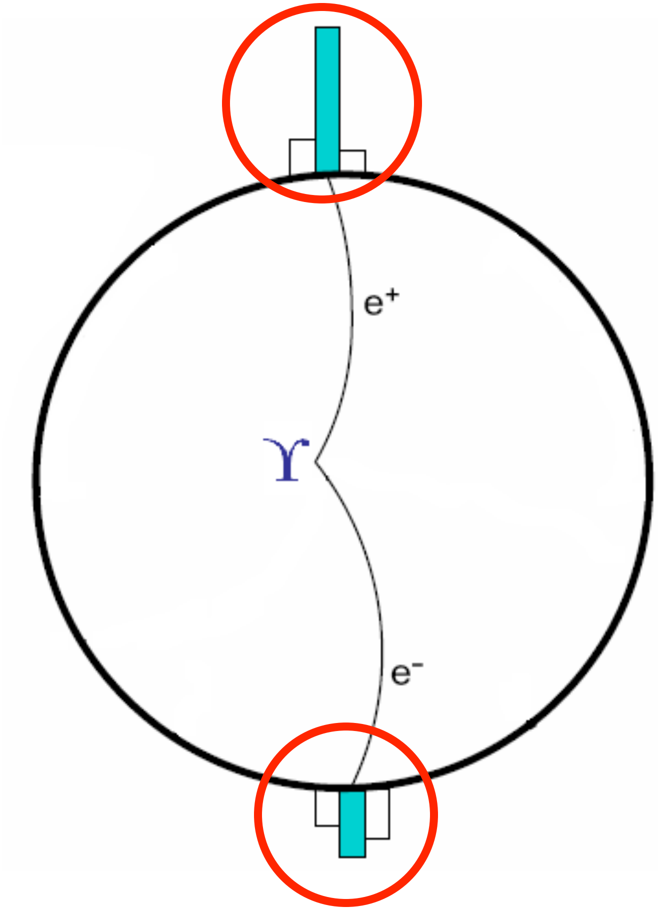


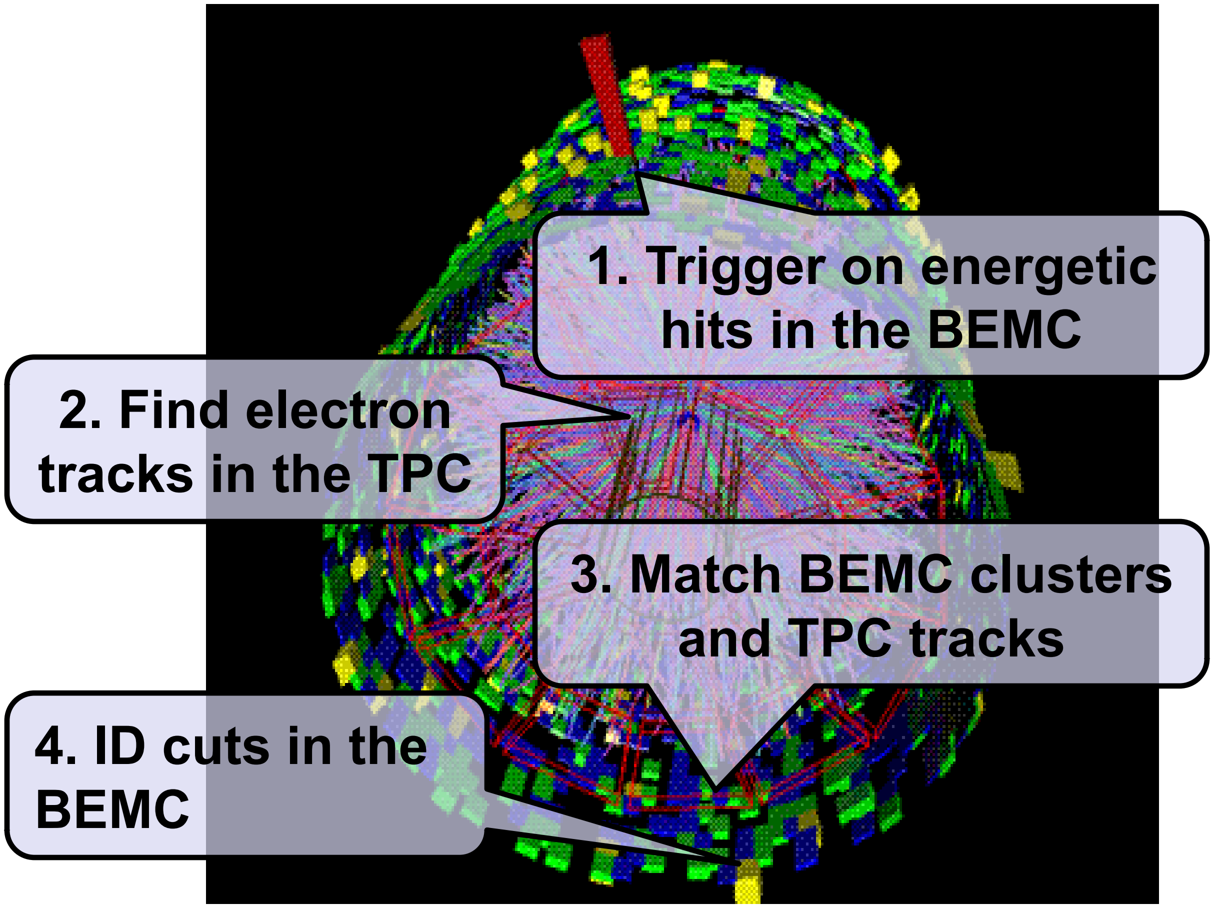
- Clusterize energy deposit in the BEMC

  Cluster: 3 adjacent towers with most of the energy deposit
- Project TPC tracks onto clusters to match them

  $\Delta R_{match} = \sqrt{(\Delta\eta^2+\Delta\varphi^2)} < 0.04$

4. ID in the calorimeter





- Cluster energy matches track momentum
  $0.75 < E/(pc) < 1.4$ *(U+U analysis)*
- Energy deposit is compact, mostly in a single tower
  triggered $e^{\pm}$: $E_{tower}/E>0.7$, associated $e^{\pm}$: $E_{tower}/E>0.5$ *(U+U analysis)*

STAR Υ measurements – summary

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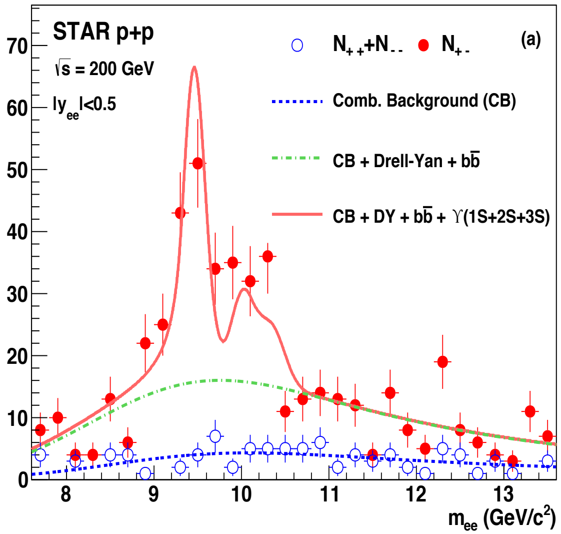

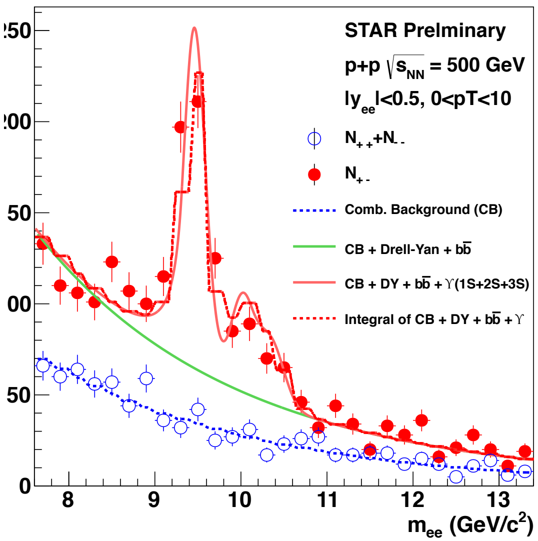

- **p+p @ 200 GeV**
- p+p @ 500 GeV
  - pQCD benchmark
  - Reference for A+A

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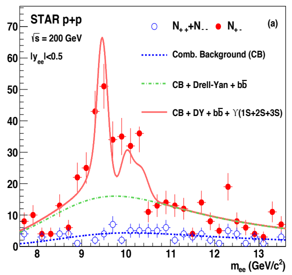

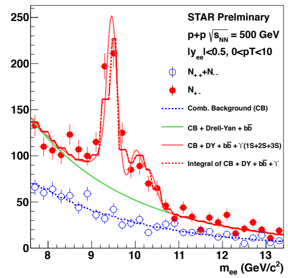

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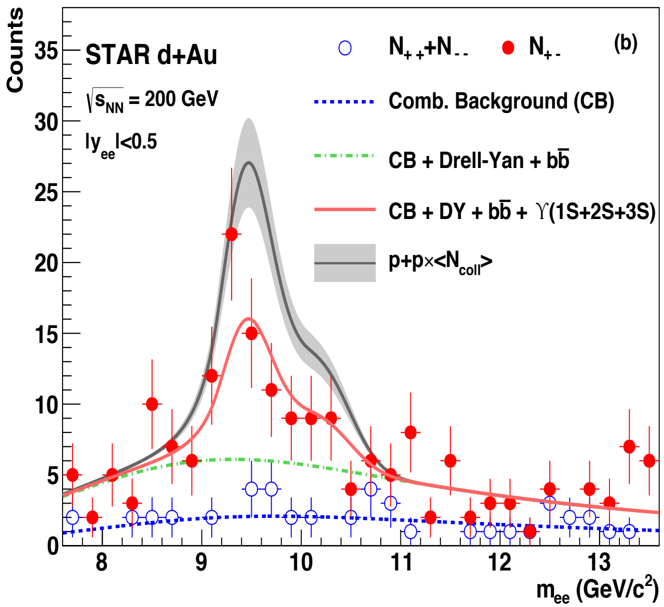

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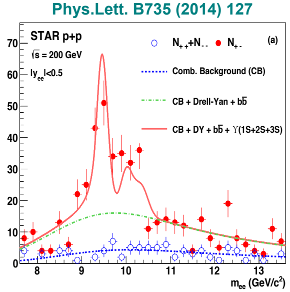

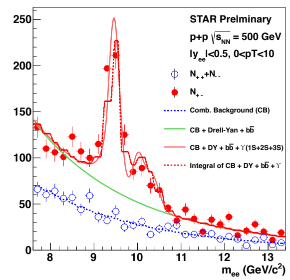

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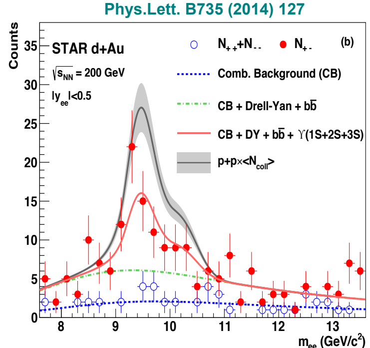

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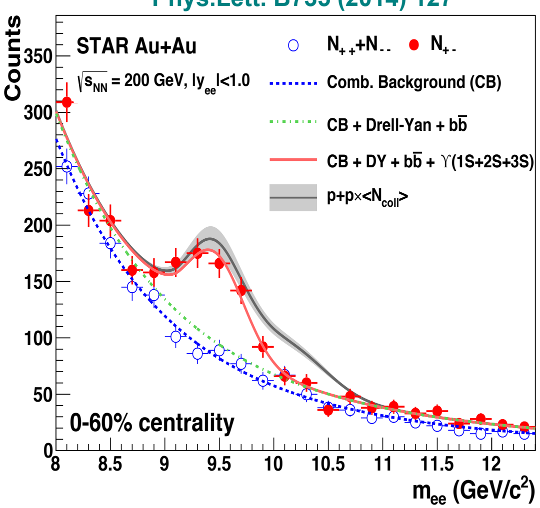

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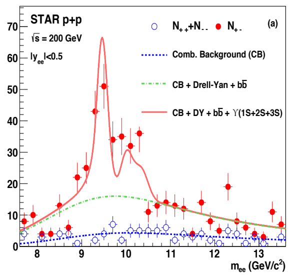

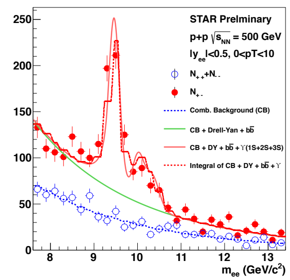

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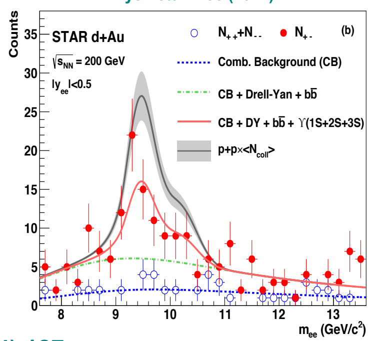

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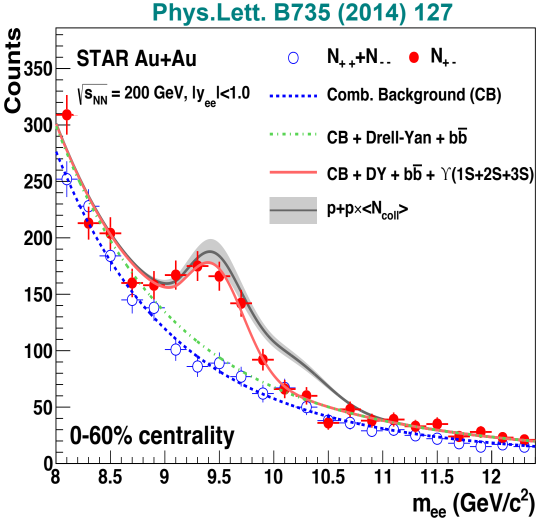

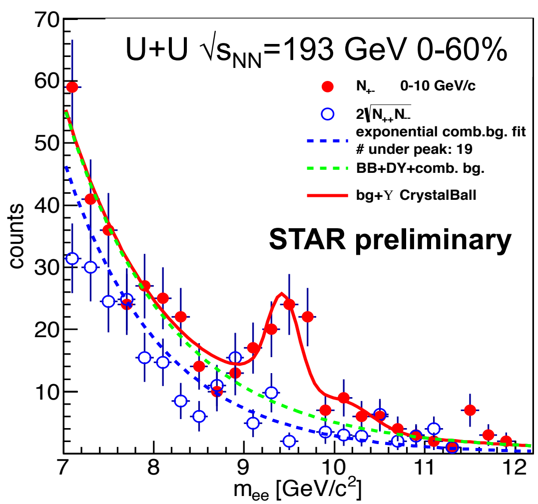

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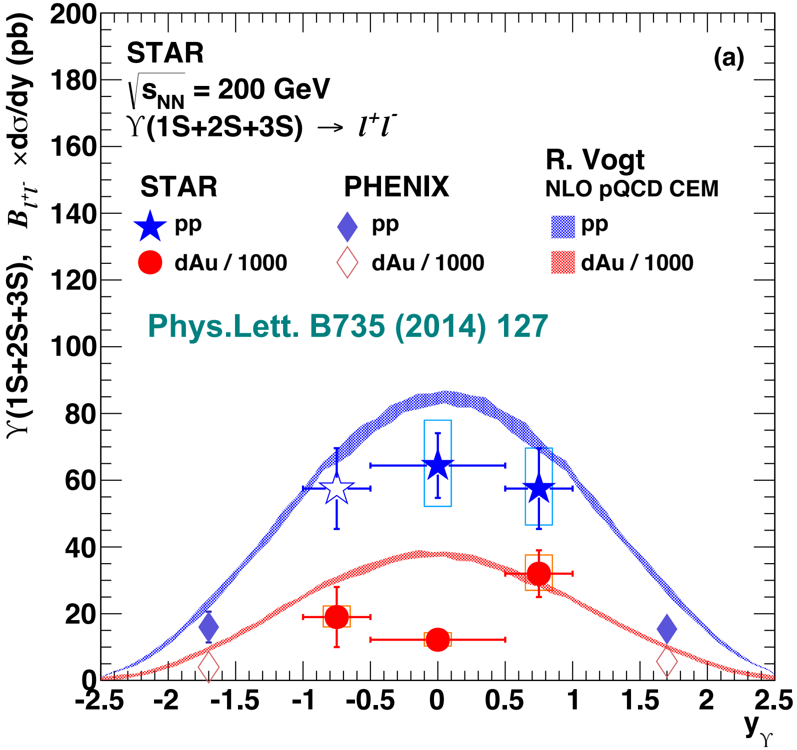
- **U+U**
  - Further tests of sequential melting
  - N_{part} dependence

Υ in p+p – baseline



- p+p Υ cross section vs. y, compared to pQCD predictions

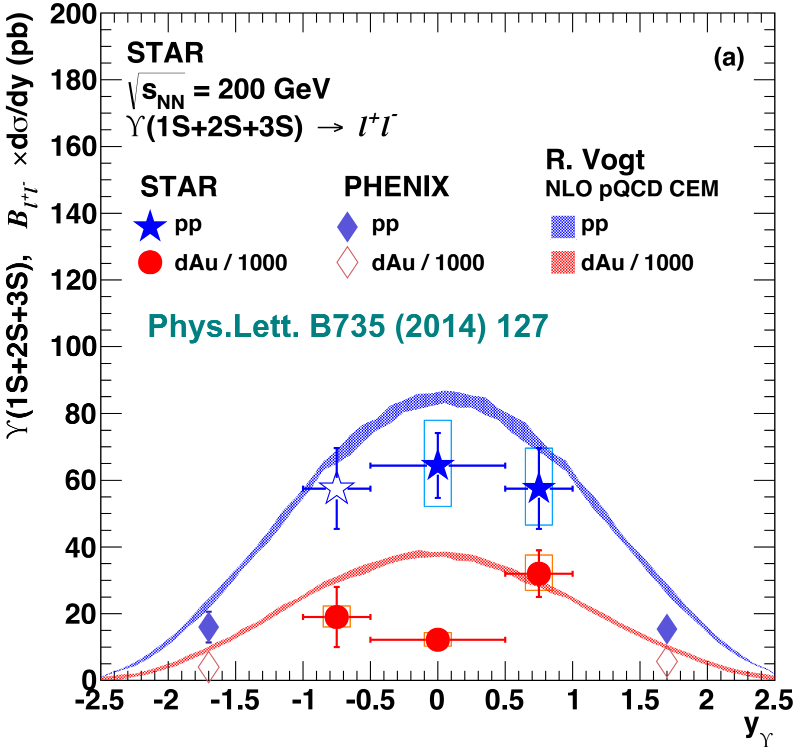
R. Vogt, Phys. Rep. 462125, 2008

Υ in p+p 200 GeV, |y|<0.5, L0 & L2

∫L dt = 20.0 pb^{-1}
N_Υ(total)= 152 ± 23 (stat. + fit)

$$\sum_{n=1}^{3} \mathcal{B}(nS) \times \frac{d\sigma(nS)}{dy} = 64 \pm 10^{+14}_{-12}\ \mathrm{pb}$$

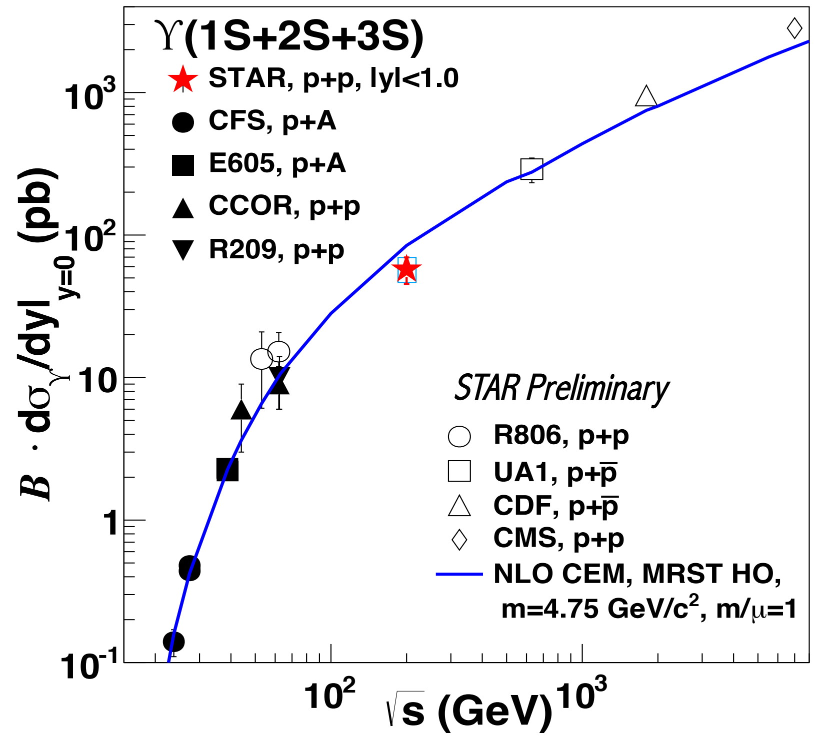
ϒ in p+p – baseline and pQCD test



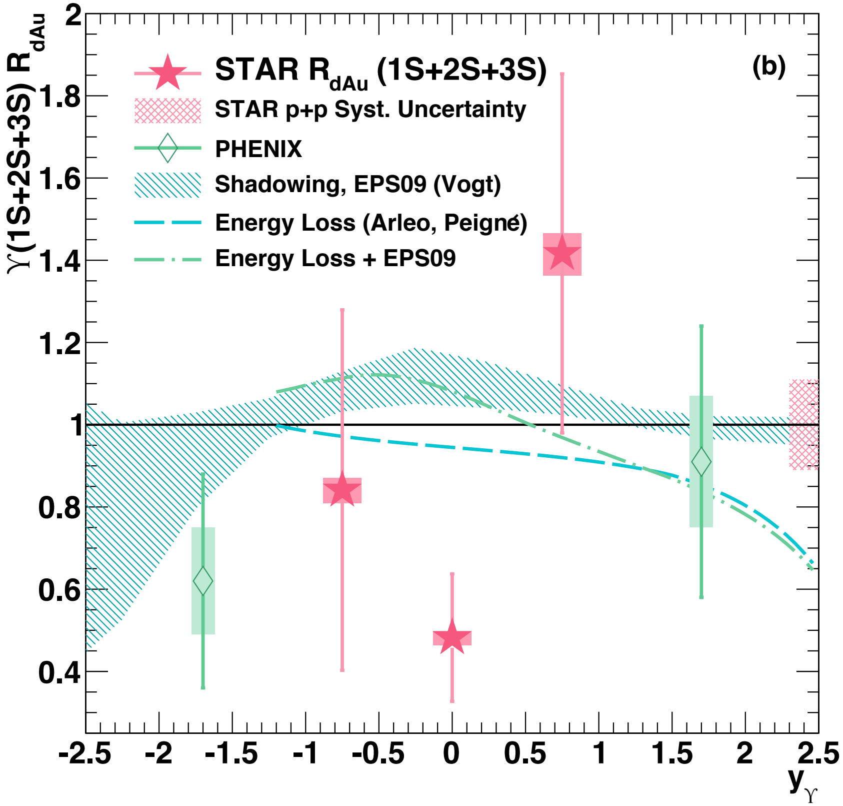
- p+p ϒ cross section vs. y, compared to pQCD predictions

R. Vogt, Phys. Rep. 462125, 2008

- p+p ϒ cross section, compared to world data trend



Υ R_{dAu} – CNM effects



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- Indication of suppression at mid-rapidity beyond models

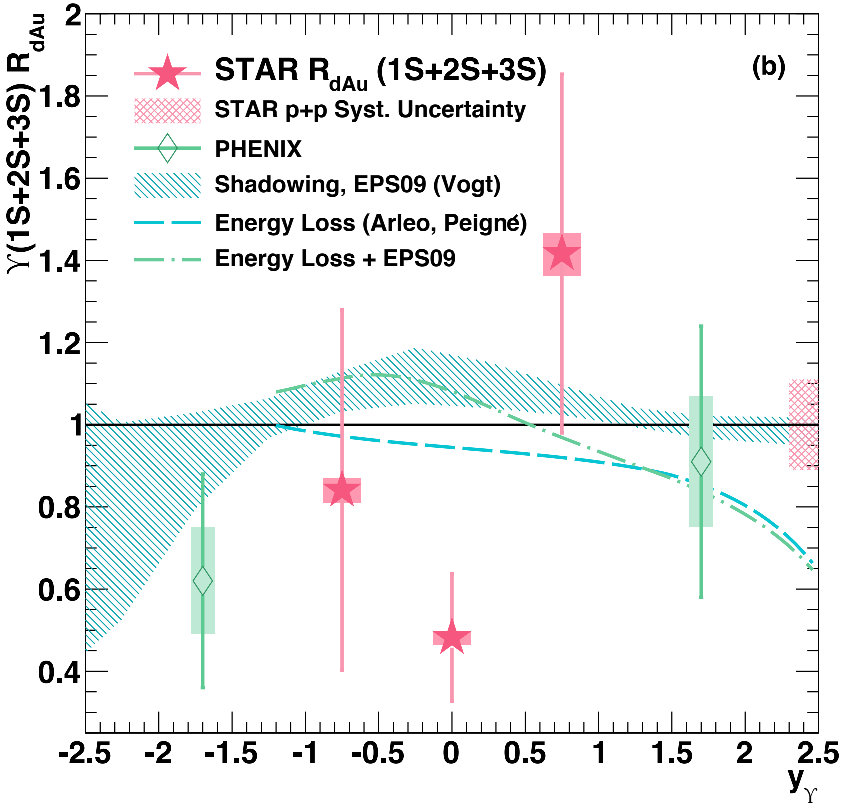
Υ in d+Au 200 GeV, |y|<0.5, L0 & L2

$\int L\,dt = 28.1\ nb^{-1}$

N_{Υ}(total)= 46 ± 13 (stat. + fit)

R_{dAu} = 0.48 ± 0.14(stat) ± 0.07(syst) ± 0.02(pp stat) ± 0.06(pp syst)

Υ R_{dAu} – CNM effects



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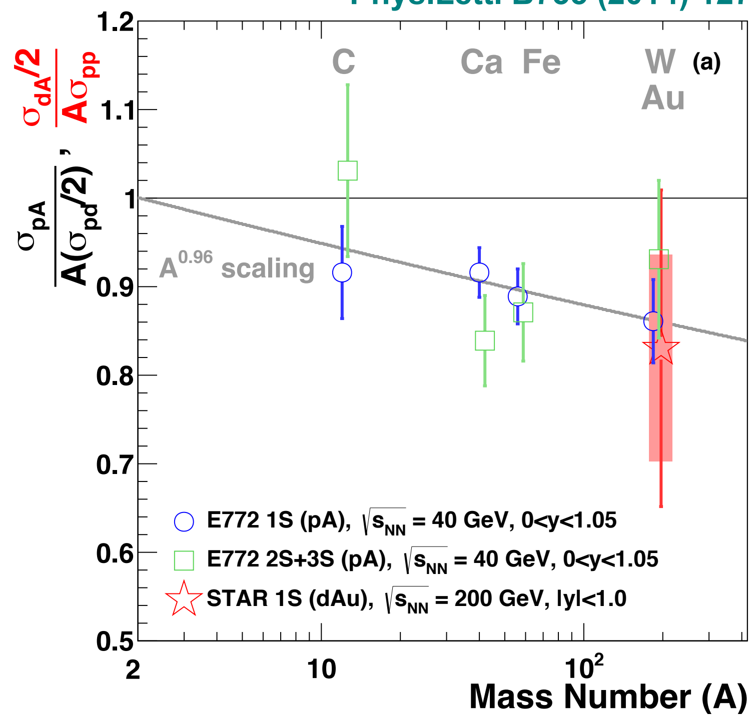
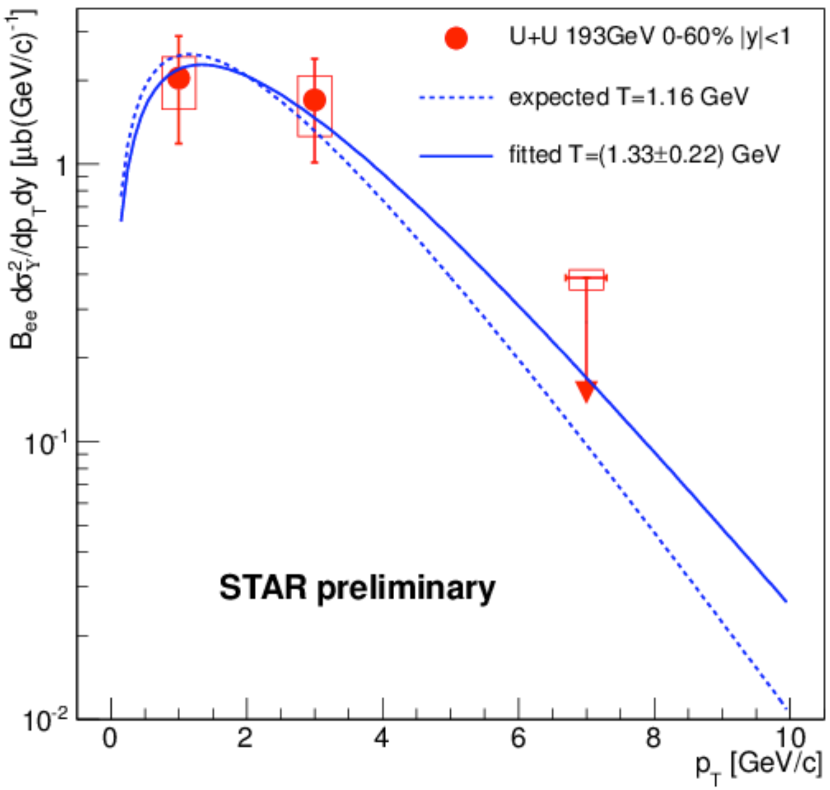


- STAR data consistent with E772 despite difference in energy

Υ x-section and p_T-spectrum in U+U

Υ spectrum



Υ cross section (STAR preliminary)

U+U 193 GeV, 0-60% centrality

$$B_{ee} \frac{d\sigma_{AA}^{\Upsilon}}{dy}\Bigg|_{|y|<1} = (4.37 \pm 1.09 \; {}^{+0.65}_{-1.01}) \; \mu b$$

stat. syst

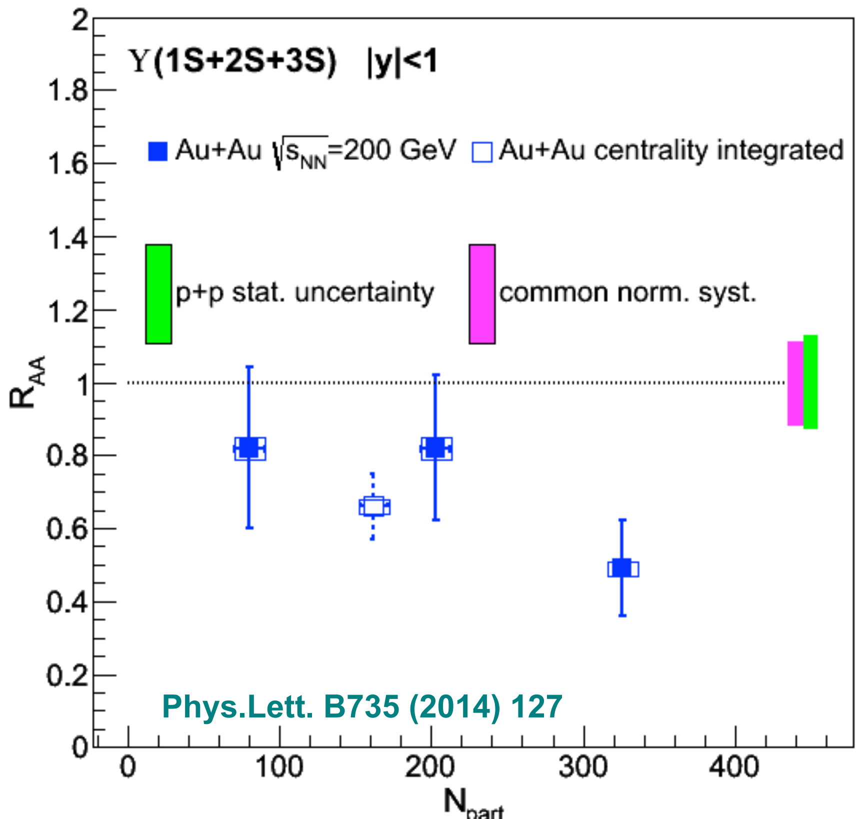
"expected" line:

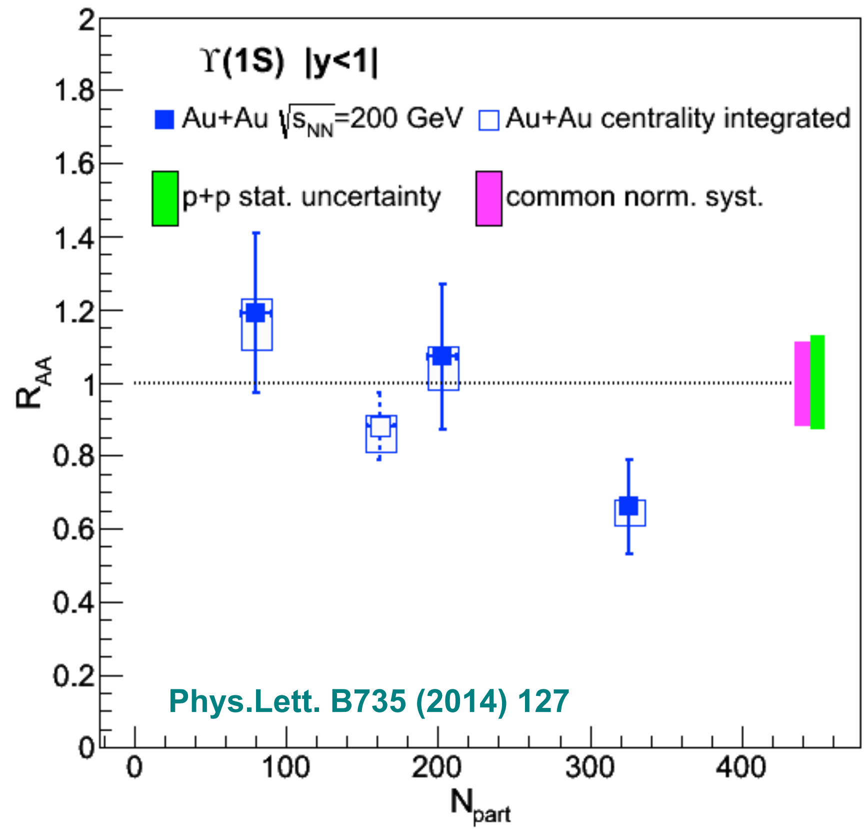
$$f(p_T) = \frac{p_T}{\exp(p_T / T + 1)}$$

T: interpolation of pp ($p\bar{p}$) results from ISR, CDF and CMS

PLB91, 481 (1980).
PRL88, 161802 (2002).
PRD83, 112004 (2011)

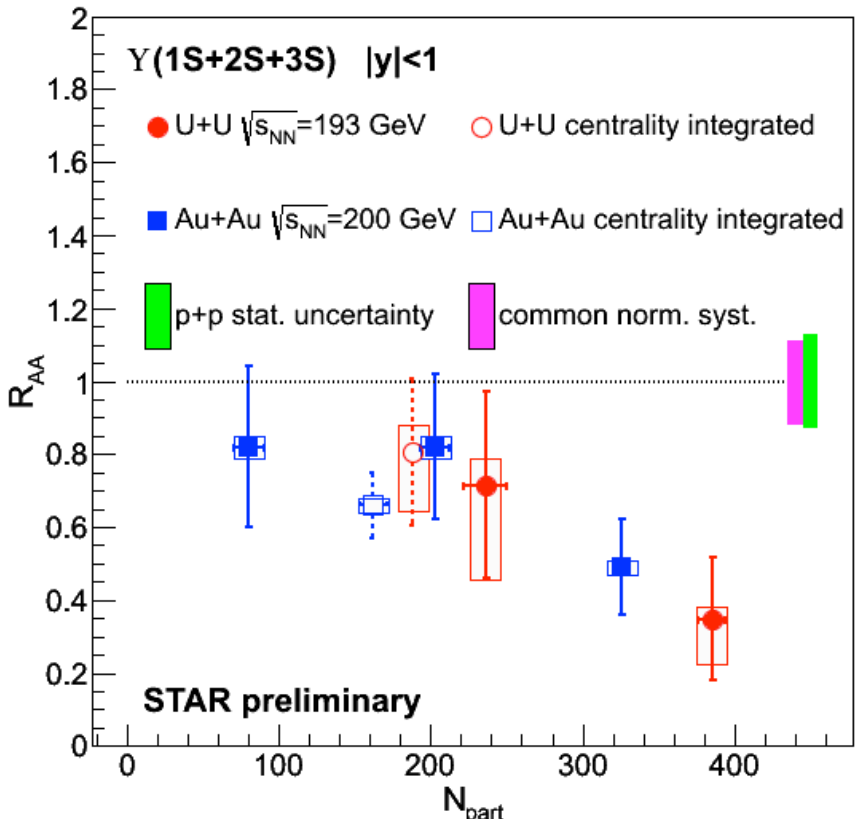
R_{AA} : Υ(1S+2S+3S) and Υ(1S)

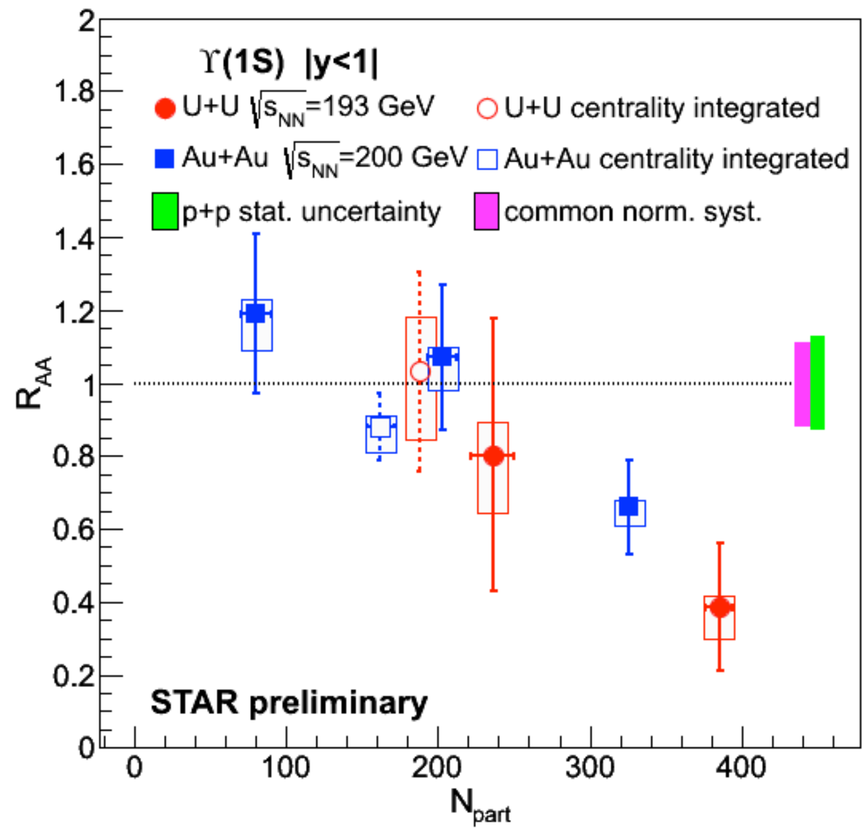




- Peripheral Υ:
  consistent with no suppression
- Central Υ:
  significant suppression
- Central Υ(1S):
  indication of a suppression

Υ R_{AA} : Au+Au vs. U+U

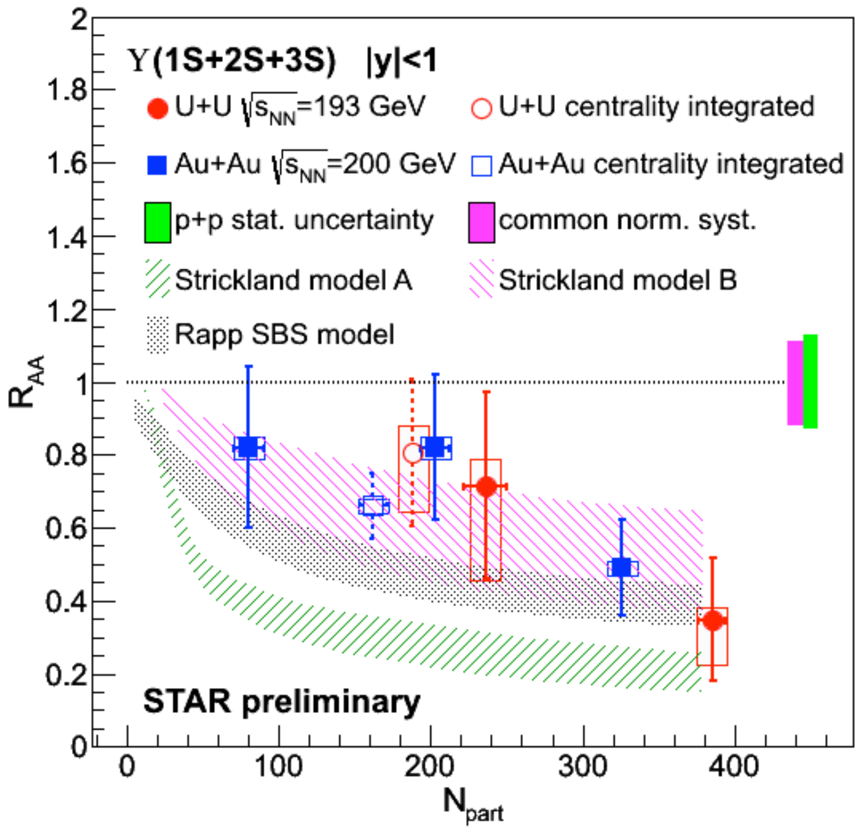


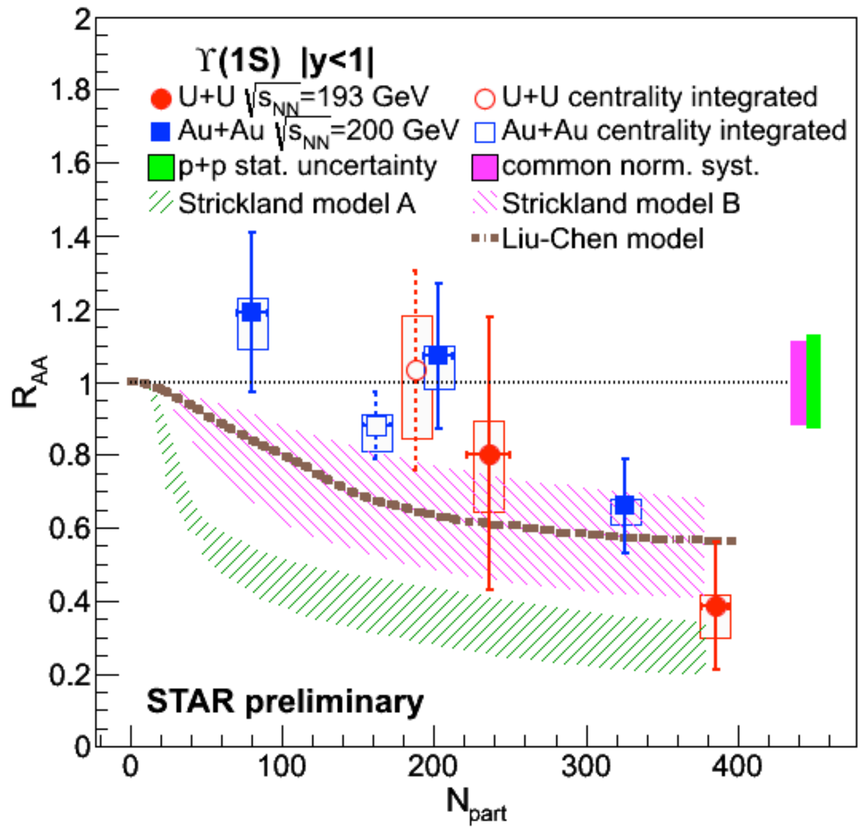


- Peripheral Υ: consistent with no suppression
- Central Υ: significant suppression
- Central Υ(1S): *significant suppression*

New U+U data confirms and extends Au+Au trend

Υ R_{AA} : data vs. models





Strickland, Bazov, Nucl.Phys.A 879, 25 (2012)

- No CNM effects, 428<T<443 MeV
- Potential model 'B' based on **heavy quark internal energy**
- Potential model 'A' based on heavy quark free energy (disfavored)

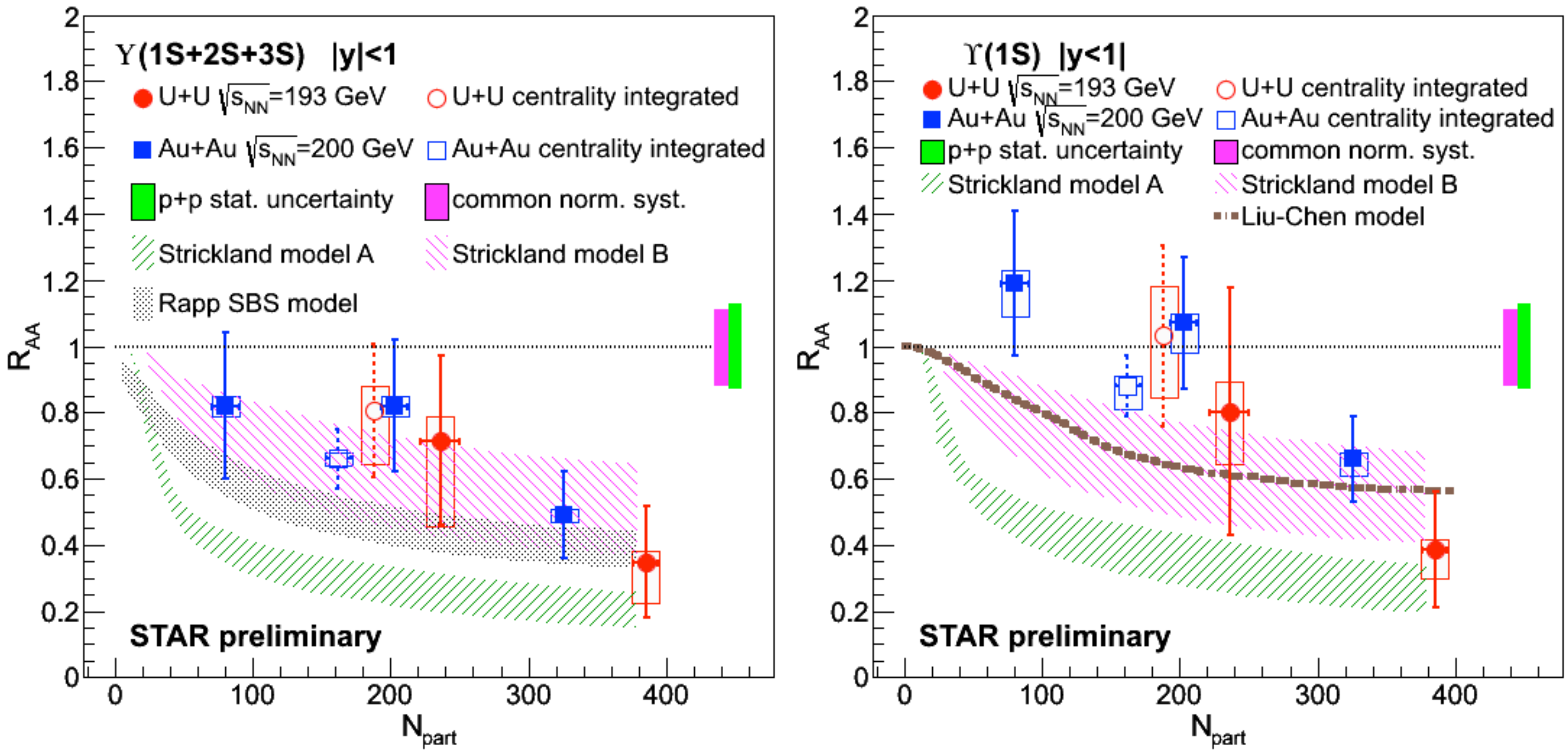
Liu, Chen, Xu, Zhuang, Phys.Lett.B 697, 32 (2011)

- Potential model, no CNM effects
- T=340 MeV, only excited states dissociate

Emerick, Zhao, Rapp, Eur.Phys.J A48, 72 (2012)

- **CNM effects** included
- Strong binding scenario

Υ R_{AA} : data vs. models

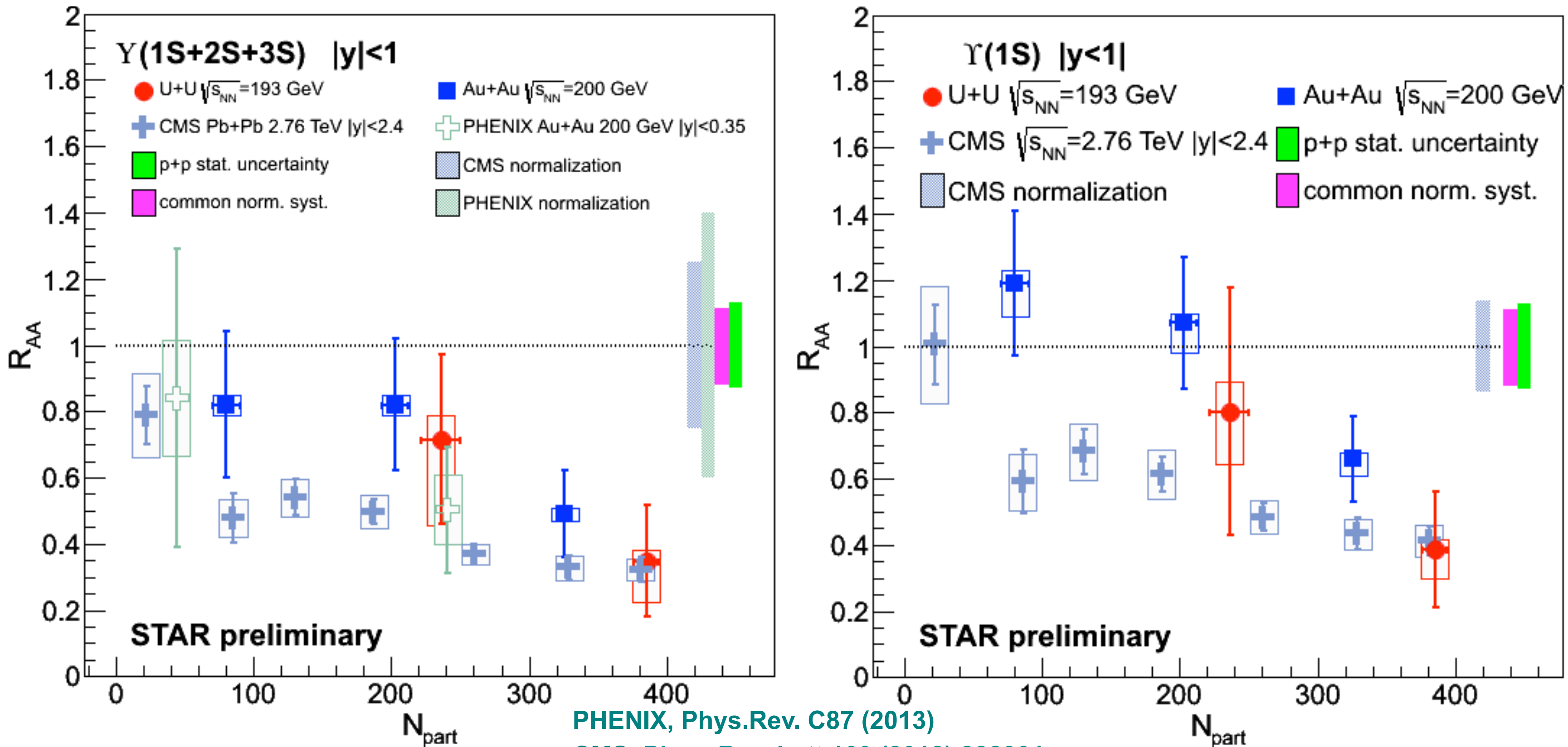


Suppression indicates Υ melting in a deconfined medium

However: CNM effects have to be understood

→ **RHIC 2015 p+Au run**

ϒ R_{AA} : RHIC & LHC comparison



PHENIX, Phys.Rev. C87 (2013)
CMS, Phys. Rev. Lett 109 (2012) 222301

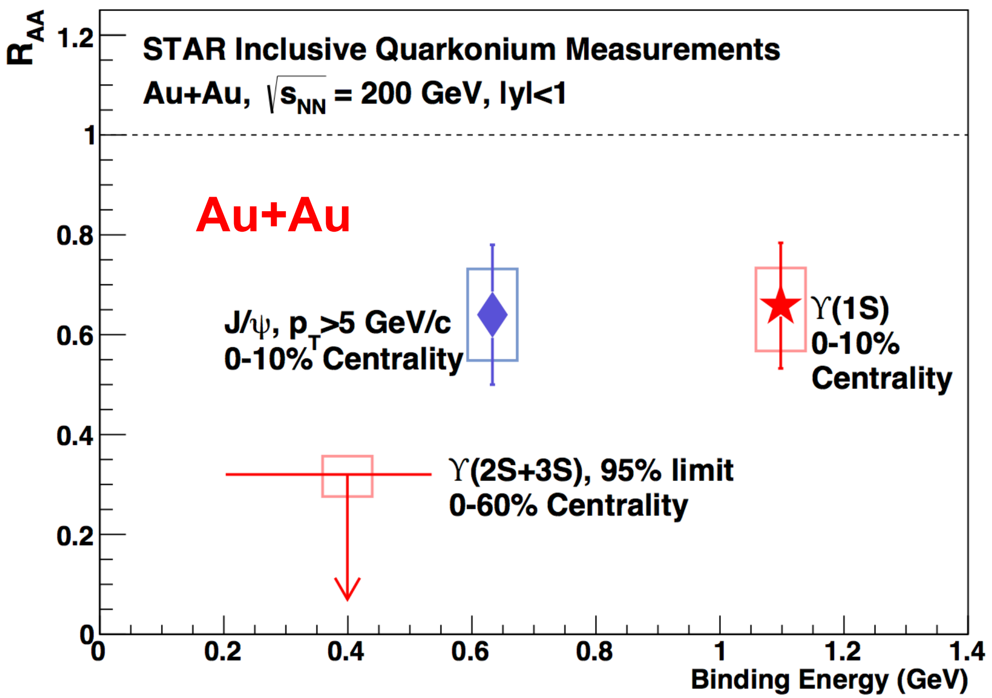
- LHC and RHIC suppressions are comparable at high N_{part}
- N_{part} dependence of ϒ suppression appears weaker at the LHC

Is suppression driven by energy density?

→*Note the uncertainties, however*

Excited Υ states in Au+Au

Phys.Lett. B735 (2014) 127

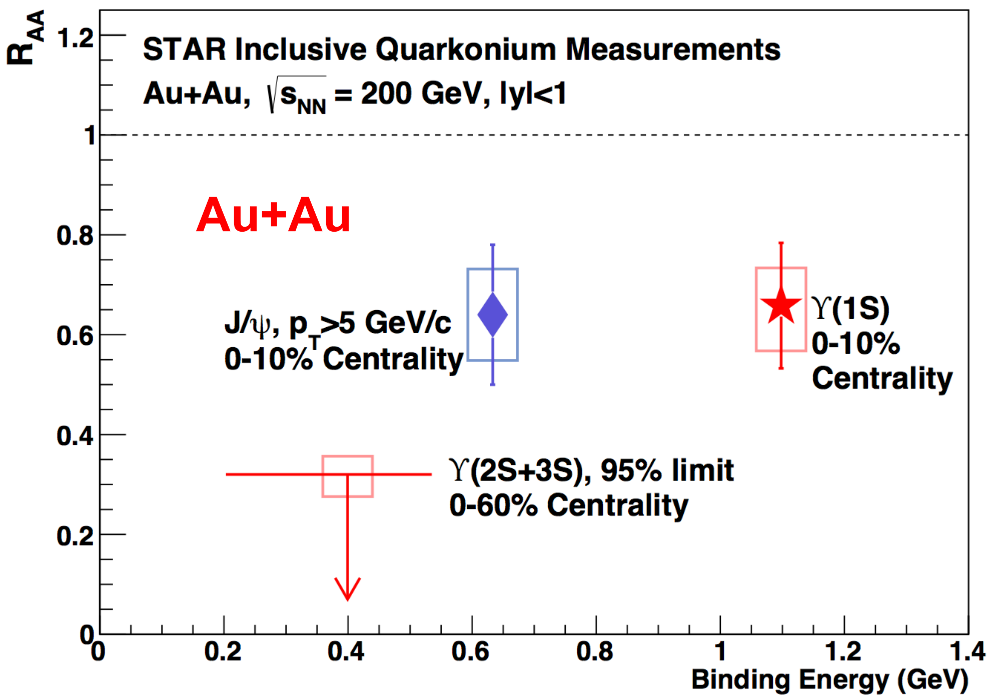


Central Au+Au:

- Excited states Υ(2S) and Υ(3S) consistent with complete melting
- Υ(1S) suppression is similar to high-p_T J/ψ

Excited Υ states in Au+Au

Phys.Lett. B735 (2014) 127



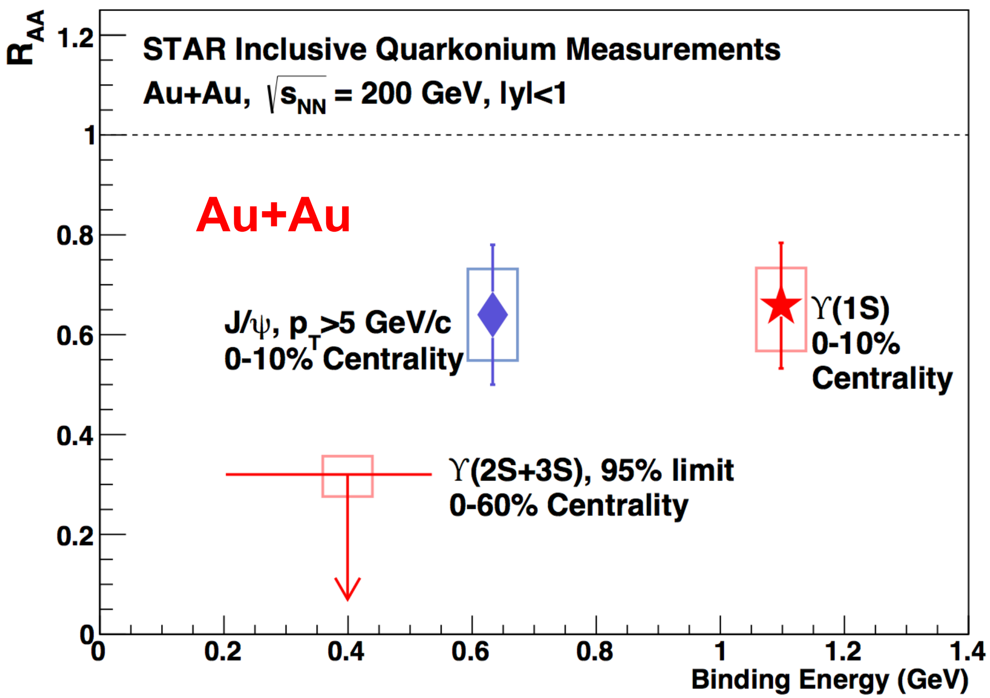
Central Au+Au:

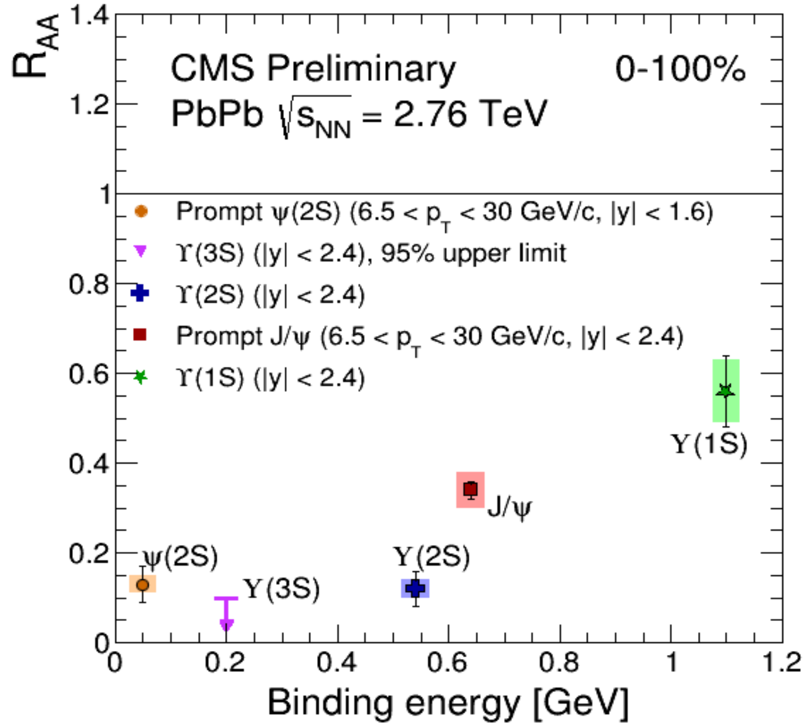
- Excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ consistent with complete melting
- $\Upsilon(1S)$ suppression is similar to high-p_T J/ψ

Υ suppression pattern supports sequential melting

Excited Υ states – LHC comparison

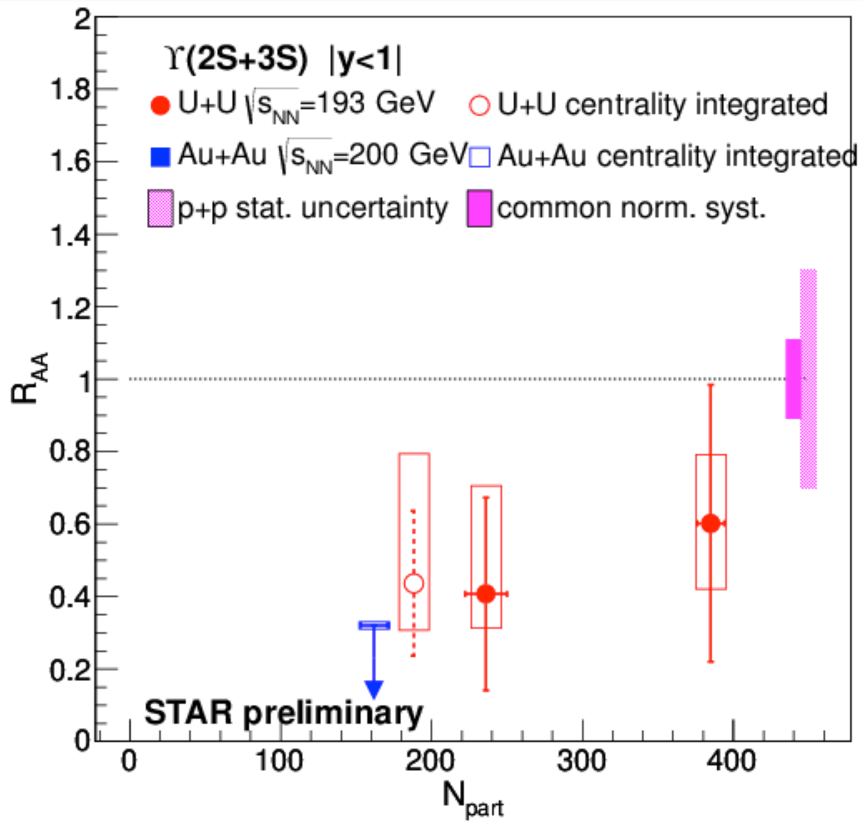
Phys.Lett. B735 (2014) 127





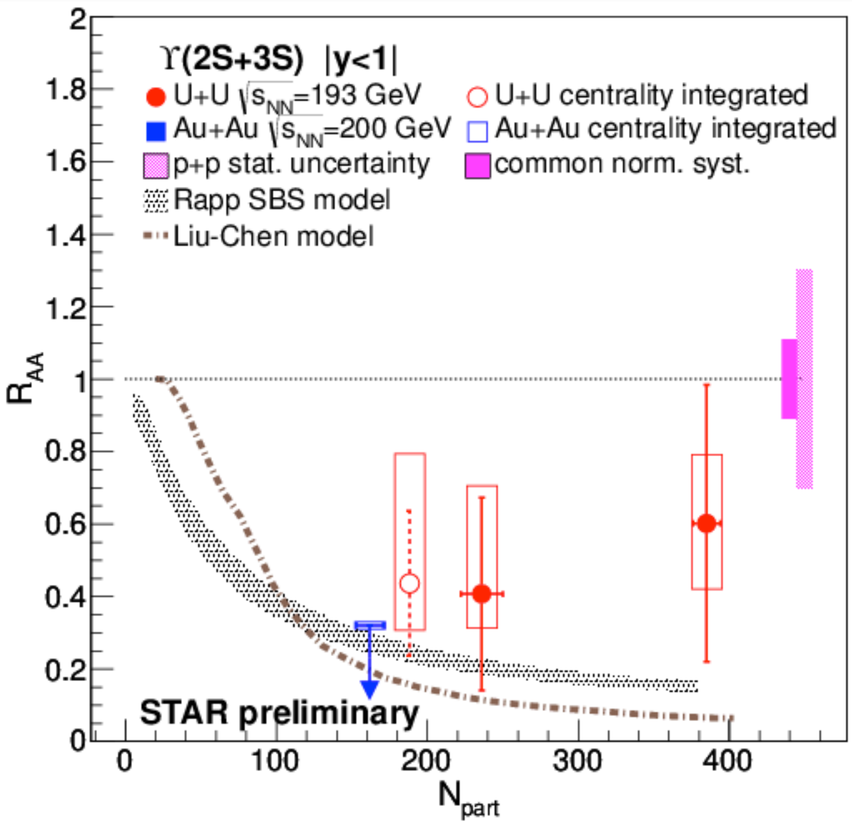
- RHIC $\sqrt{s_{NN}}$=200 GeV Au+Au and LHC $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb collisions: Similar suppression of central $\Upsilon(1S)$

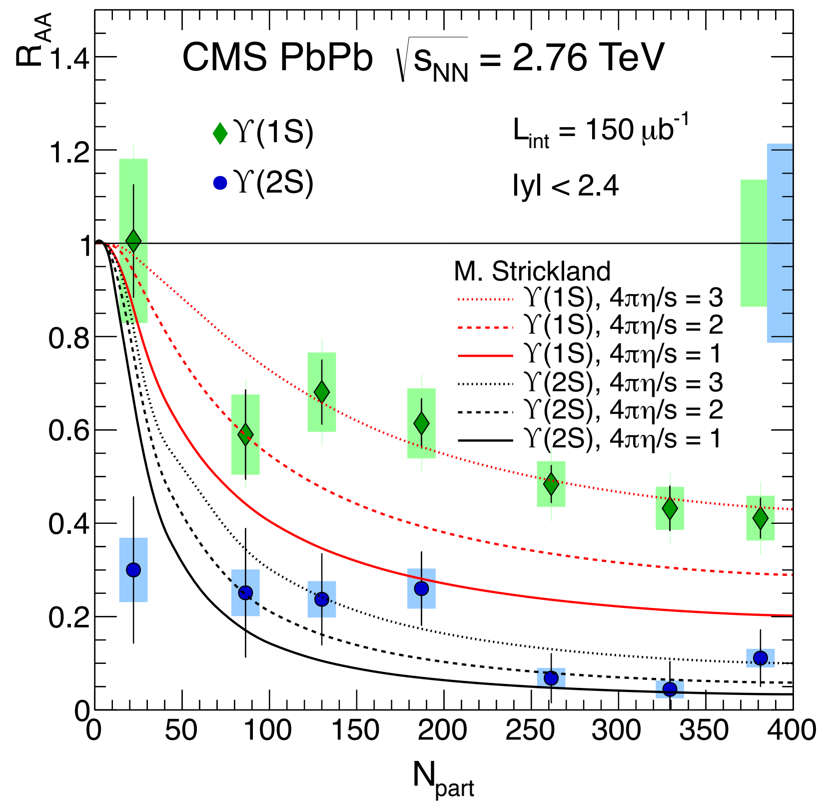
Excited Υ states, U+U



- U+U consistent with Au+Au limit, but…
- 0-60% centrality: R_{AA}(2S+3S)>0 at the 1.8σ level

Excited Υ states, comparison





- U+U consistent with Au+Au limit, but…
- 0-60% centrality: R_{AA}(2S+3S)>0 at the 1.8σ level
- Consistent with 2S model trend and LHC measurement

Is U+U different?

Summary

CNM effects: Υ suppression in d+Au has to be understood

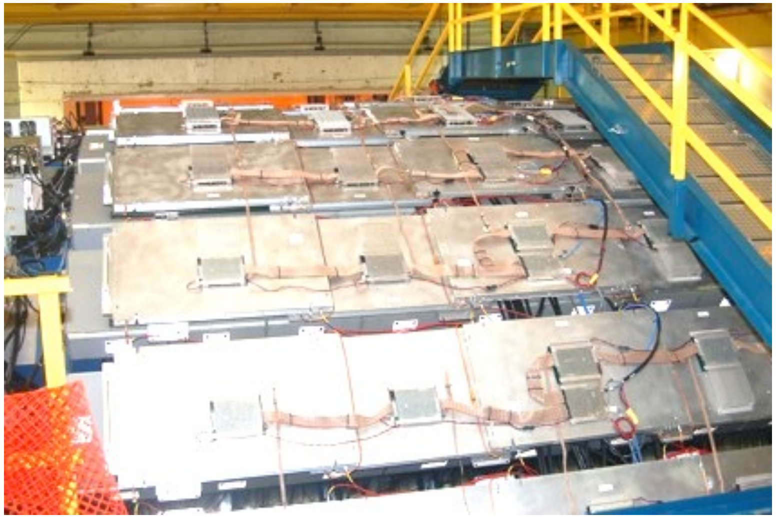
Hot medium effects: Significant suppression of Υ states in central A+A collisions

- Υ(1S) is similarly suppressed as high-p_T J/ψ
- Υ(2S) and Υ(3S) suppression is stronger than Υ(1S)
  → *clear signal of melting in a deconfined medium*
- Υ suppression in most central collisions similar to LHC

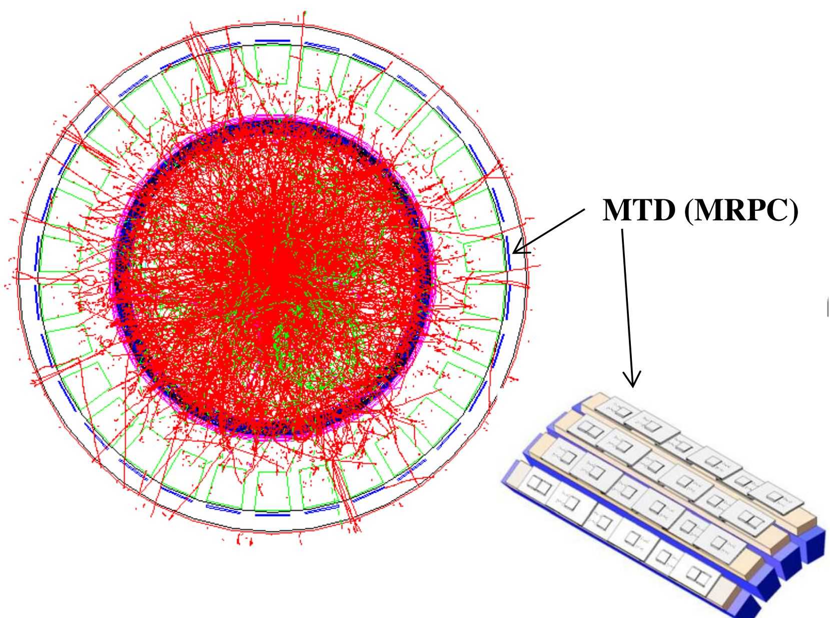
U+U measurements: extends the Au+Au observations

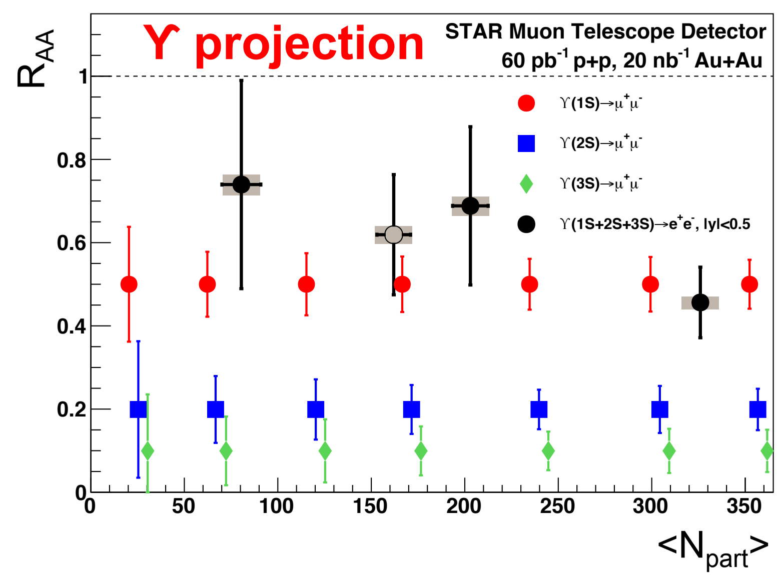
- Similar patterns in Υ(1S) and Υ(1S+2S+3S)
- Suppression of central Υ(1S) confirmed
- Indication of Υ(2S+3S) presence in 0-60% data (1.8σ effect)

Outlook: Muon Telescope Detector



- Outermost, gas detector
- Physics goal: **Precision measurement of heavy quarkonia through the muon channel**
- Acceptance:
  45% in azimuth, |y|<0.5

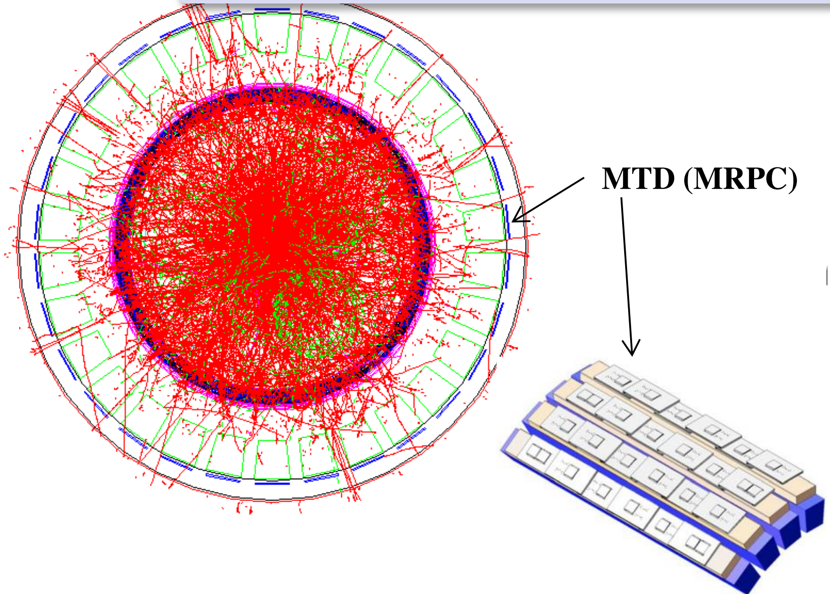


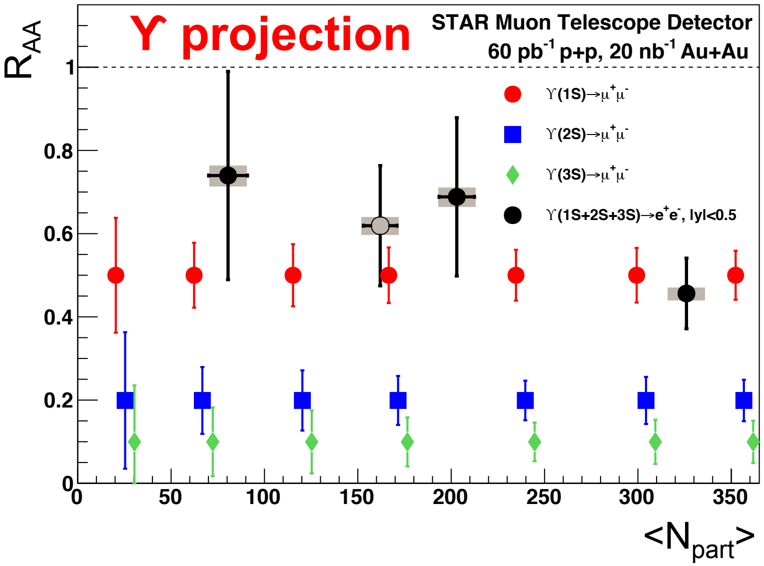


Outlook: Muon Telescope Detector

- Outermost, gas detector
- Physics goal: **Precision measurement of heavy quarkonia through the muon channel**
- Acceptance: 45% in azimuth, |y|<0.5

~13.8 nb^{-1} Au+Au data from 2014 – being analyzed





Thank You!

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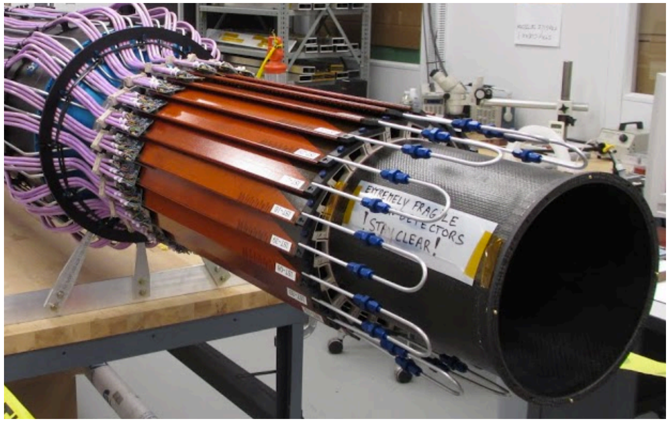
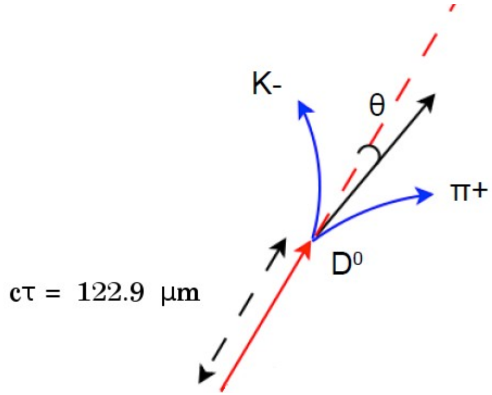
STAR Collaboration

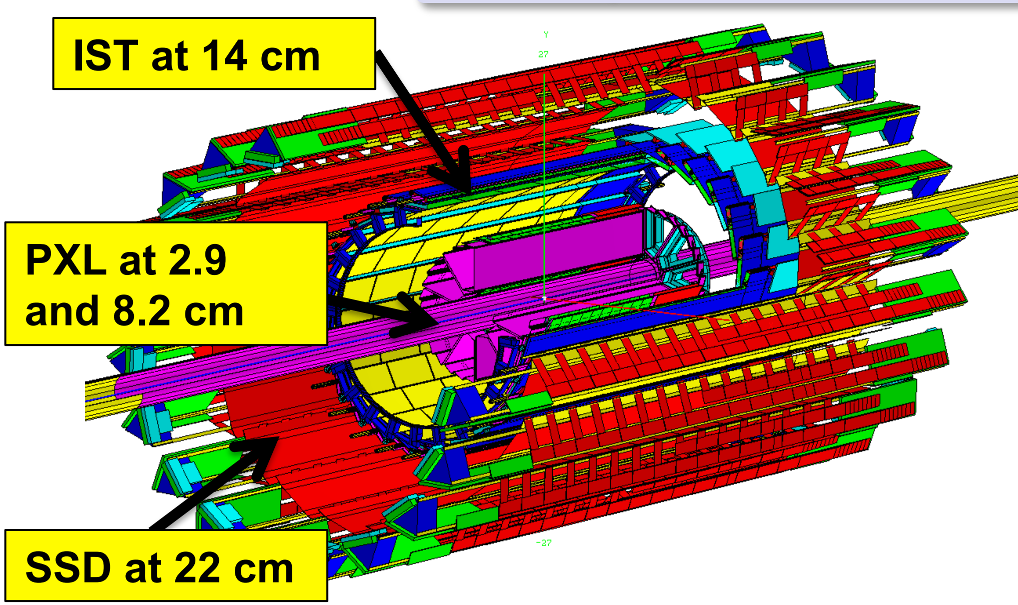
Outlook: Heavy Flavor Tracker

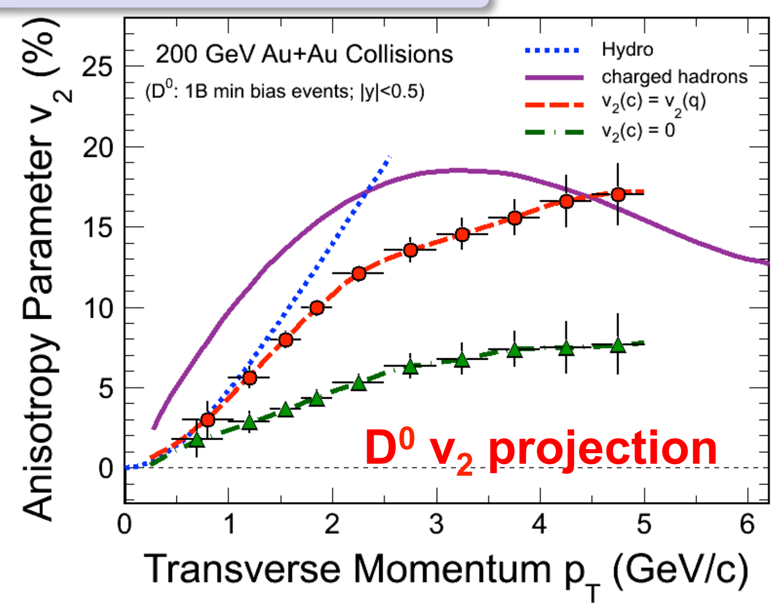




- Innermost, silicon detectors (3 subsystems)
- Resolves secondary vertex
- Physics goal: **Precision measurement of heavy quark production**

Complete and taking data in Run14



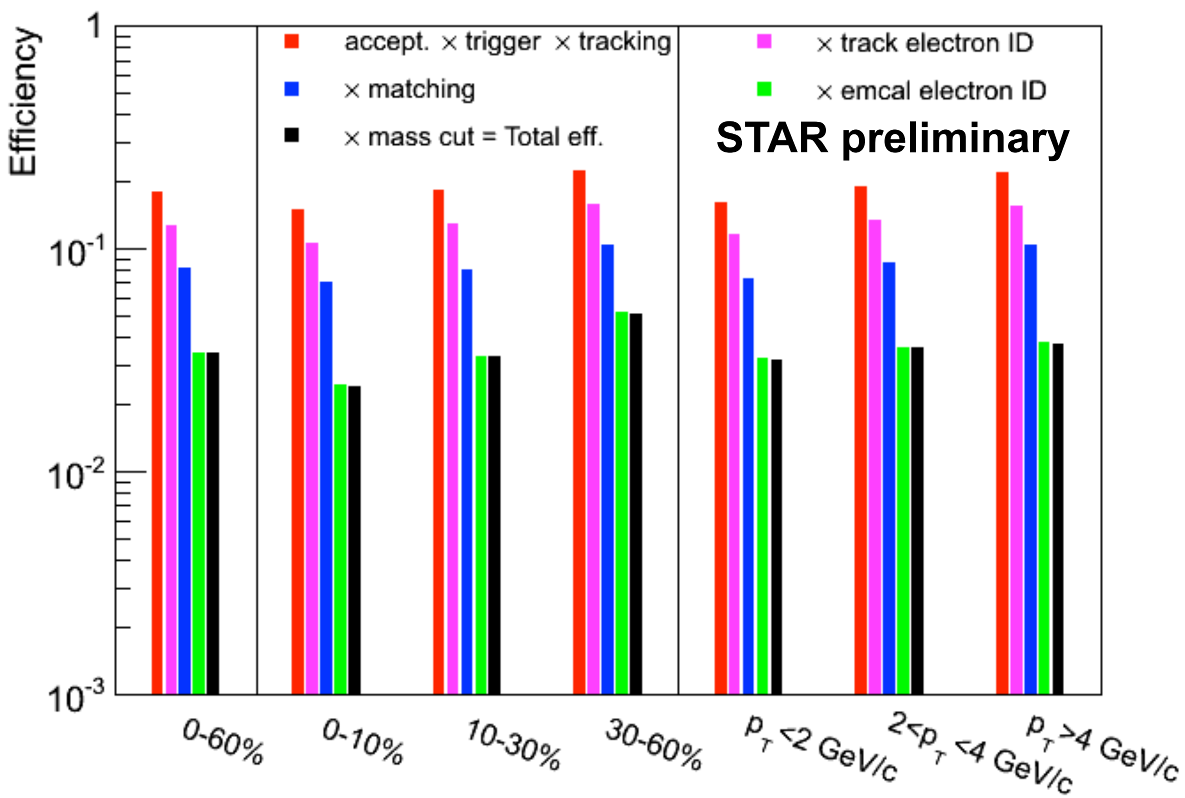


U+U acceptance and efficiency

- 15M high-tower-triggered U+U 193 GeV events (263 μb^{-1})

- Divided into 3 centrality bins:
  - 0 – 10 %
  - 10 – 30 %
  - 30 – 60 %

- or… 3 bins in p_T^{Υ}:
  - 0 – 2 GeV/c
  - 2 – 4 GeV/c
  - 4< GeV/c



- Total acceptance & efficiency for $\Upsilon \rightarrow e^+e^-$ reconstruction: ~ 2-3%

Rapp WBS & SBS

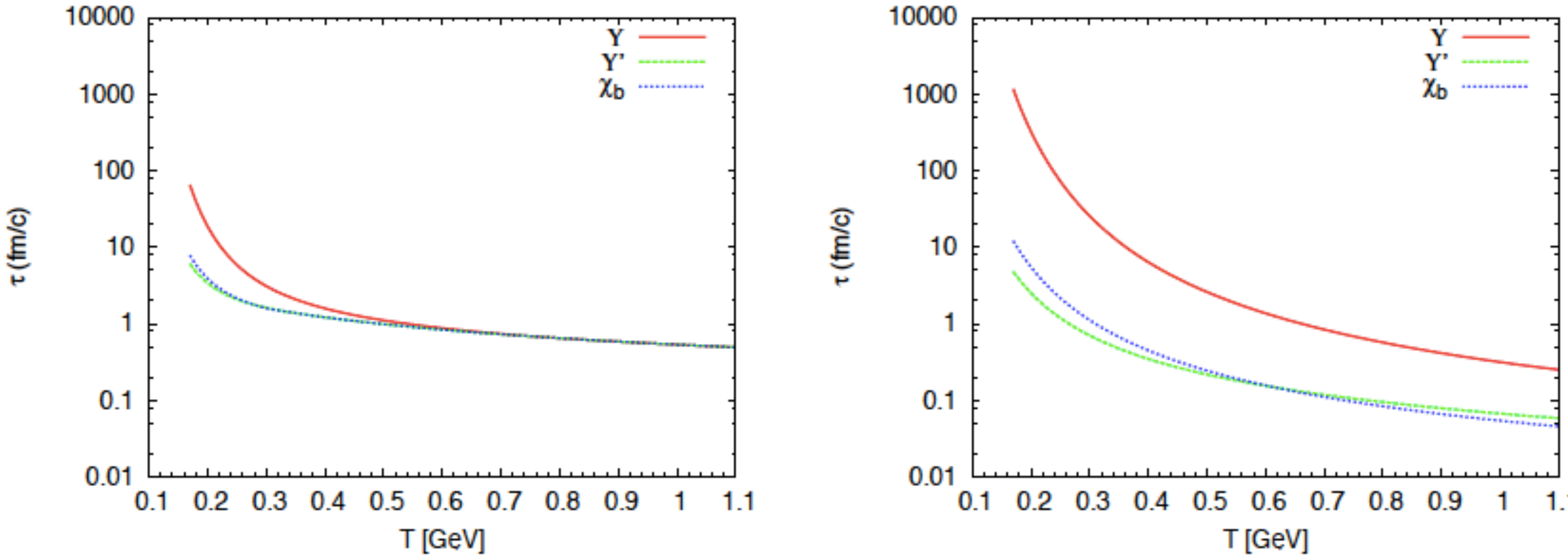
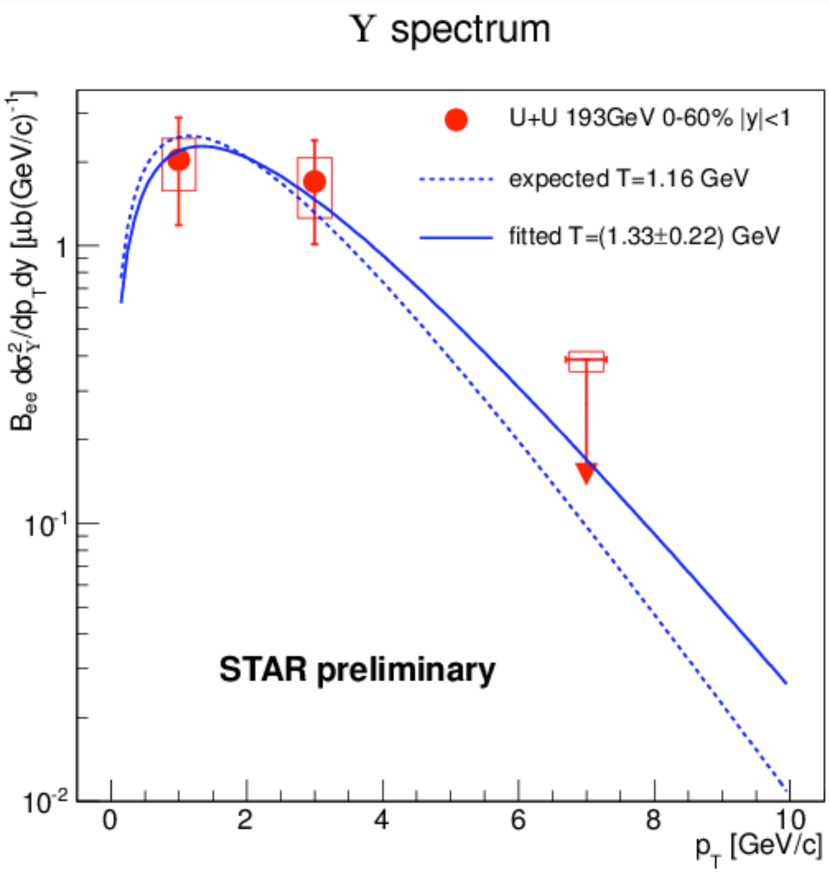


FIG. 2: Bottomonium lifetimes in the QGP for the two binding scenarios defined in the text; left panel: WBS with quasifree dissociation; right: SBS with gluo-dissociation; solid lines: Υ, dashed lines: Υ', dotted lines: χ_b.

- **Emerick, Zhao, Rapp, Eur. Phys. J A48, 72 (2012)**

ϒ x-section and p_T-spectrum in U+U



$$f(p_T) = \frac{p_T}{\exp(p_T/T+1)}$$

Expected T is extrapolated from ISR, CDF and CMS pp ($p\bar{p}$) results

PLB91, 481 (1980).
PRL88, 161802 (2002).
PRD83, 112004 (2011)

ϒ cross section (STAR preliminary)

U+U 193 GeV, 0-60% centrality

$$B_{ee}\left.\frac{d\sigma^{\Upsilon}_{AA}}{dy}\right|_{|y|<1} = (4.37 \pm 1.09 \; {}^{+0.65}_{-1.01}) \; \mu b$$

stat. syst

Major systematic uncertainties (%) (STAR preliminary)

Geometrical acceptance	+1.7 -3.0
Trigger efficiency	+1.1 -3.6
Tracking efficiency	11.8
TPC electron identification	+4.0 -6.4
TPC-BEMC matching	5.4
BEMC electron identification	5.9
Embedding p_T and y shapes	2.1
Signal extraction	+4.8 -18